Report of the NSF Elementary Particle Physics

Special Emphasis Panel on B Physics

This report represents the opinions of the Special Emphasis
Panel, which are not necessarily those of NSF.

July, 1998

1 Executive Summary

The Special Emphasis Panel met to study the opportunities for the Elementary Particle Physics program of NSF in the burgeoning field of B physics. Representatives of the CDF, D0, HERA-B, BaBar, CLEO, BTeV, and LHCb collaborations presented summaries of their programs and plans.

B physics tests a critical element in the Standard Model of particle interactions, which predicts that weak decays of hadrons containing b quarks are governed by the Cabibbo-Maskawa-Kobayashi matrix. The four physical parameters of the CKM should account for all b decay phenomena, including the anticipated CP violation. To determine whether this is so requires a very broad range of measurements.

Both e^+e^- colliders and hadron machines will participate in the next phase of the B-physics program, starting in 1999-2000. In some areas, the two approaches compete directly, in others one approach or the other has a distinct advantage. None of the experiments beginning at that time will be able to answer all the fundamental questions of B physics. A subsequent phase with higher luminosity e^+e^- machines and detectors specifically designed for B physics at hadron colliders will be required to give a final answer to the adequacy of the CKM matrix explanation of weak interactions and CP violation.

The NSF program in particle physics has already made enormous contributions to B physics, especially at Cornell, where much has been learned about the magnitudes of various elements of the CKM matrix. The Panel believes that B physics should continue to be a major focus of the EPP program.

The Panel recommends for the B-physics program that:

- *Full exploitation of the CESR and CLEO upgrades be the highest priority in the immediate future.*

- *NSF should support efforts in both hadron-collider and e^+e^- experiments to explore B physics in the period extending to 2005 and beyond. In particular*

  - Investments should be made in research at CESR to evaluate the prospects for a very high luminosity upgrade, to
    $\mathcal{L} = 3 \times 10^{34} \mathrm{cm}^{-2}\mathrm{s}^{-1}$.

– Investments should be made in BTeV to enhance the research and development of the challenging technical components required for this very ambitious but promising program.

- *Around 2001 any proposal from CESR for a luminosity upgrade should be evaluated in the context of the experience of the asymmetric B-factories. If the CESR proposal provides better opportunities than those that would be provided by other e^+e^- machines, NSF should strongly pursue the upgrade.*

- *Around 2001, a full technical and scientific evaluation of the BTeV experiment should be conducted. If Fermilab proceeds with the BTeV project and if it is competitive with international alternatives, NSF should give it strong support.*

- *NSF's support of current B-physics research programs (BaBar, CDF, D0, HERA-B) is fully warranted. Arguments for increasing NSF support for the HERA-B program were not persuasive.*

2   Charge to the Panel and its Organization

The Panel was asked by NSF to address the charge:

> The study of B particles is an increasingly important component
> of the national and international high-energy physics program.
> Within the next two or three years, current experiments will be
> joined by new major efforts designed to study the properties of
> B decays, and especially CP violation. Requests to participate in
> these programs may well exceed the capability of the Elementary
> Particle Physics program at NSF to fund them. The program asks
> the Special Emphasis Panel to assess the opportunities for fun-
> damental discoveries in B physics and to identify the approaches
> that are the most suitable for support by EPP over the next five
> years.

Marvin Goldberg and Patricia Rankin, the Program Directors for Ele-
mentary Particle Physics at NSF, and Boris Kayser, Program Director for
Theoretical Physics, were present. Marcel Bardon, Director of the Physics
Division of NSF, addressed the Panel at its opening session.

Representatives of major B-physics experiments – BaBar, BTeV, CDF,
CLEO, D0, HERA-B, and LHC-B – were invited to make presentations.
The meeting occurred on January 15 and 16, 1998. The agenda is shown in
Table 1.

3   B-Physics Issues and Objectives

3.1   Context

3.1.1   The flavor problem.

The understanding of fundamental forces of Nature has taken great strides
in the past 40 years. A theory of weak interactions, formulated in 1957, was
unified with electromagnetism about 10 years later. The strong interactions
were put on a firm theoretical footing through the development of quantum
chromodynamics (QCD) in the 1970's. Charmed particles, predicted in the
electroweak theory, were discovered shortly thereafter. The carriers of the
weak force, the $W^{\pm}$ and Z, were first observed in 1983. Three families of

January 15, 1997			
8:00	-	8:30	Executive Session
8:30	-	9:30	CDF
9:30	-	10:30	D0
10:30	-	11:00	Break
11:00	-	noon	HERA-B
noon	-	1:00	Lunch
1:00	-	2:00	BaBar
2:00	-	3:30	Cornell
3:30	-	4:00	Break
4:00	-	5:00	BTeV
5:00	-	6:00	LHC-B
January 16, 1997			
8:30	-	noon	Executive Session with possible call-backs of collaboration representatives
noon	-	1:00	Lunch
1:00	-	5:00	Executive Session

Table 1: Agenda for the meeting of the Special Emphasis Panel on B Physics of the NSF Elementary Particle Physics program.

quarks and leptons have now been established through the discovery of the tau (τ) lepton in 1975, the "bottom" or "beauty" quark b in 1977, and the top (t) quark in 1995.

This "standard model" of the elementary particles is nonetheless incomplete. The breaking of electroweak symmetry, whereby the $W^{\pm}$ and Z acquire masses while the photon remains massless, is described but not understood. The search for the "Higgs boson" or other signatures of electroweak symmetry breaking is a prime motivation for many present experiments pursued now at Fermilab and LEP, and planned at the Large Hadron Collider (L-HC). The masses of quarks and leptons and their weak interactions with one another are even more of a mystery, hinting at another level of description that remains to be discovered. This last question, often known as the "flavor problem," is one of the most pressing facing particle physics today.

An assault on the flavor problem for leptons is being made on many fronts through the search for neutrino oscillations, and other possibilities exist in sensitive searches for transitions between muons and electrons. In the case of quarks, unprecedented opportunities now exist for exploring the flavor problem through the study of particles containing the b quark. In the present section we outline this physics.

3.1.2   Weak b Decays.

The weakly decaying particles containing the b quark observed so far are $B^{+} = \bar{b}u$, $B^{0} = \bar{b}d$, $B_s = \bar{b}s$, $\Lambda_b = bud$ and the corresponding antiparticles. There is circumstantial evidence for the $B_c = \bar{b}c$ and for $\Xi_b^0 = bsu$ and $\Xi^{-} = bsd$, as well. The b quark decays through its coupling to the (u, c, t) quarks with the emission or absorption of a $W^{\pm}$. The couplings between (u, c, t) and (d, s, b) are described by the unitary 3×3 *Cabibbo-Kobayashi-Maskawa* (CKM) matrix [**?**, **?**]

$$V \equiv \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \simeq \begin{bmatrix} 1 - \frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{bmatrix} , \tag{1}$$

where we use an approximate parameterization [**?**] to exhibit the dependence of V on four real parameters. (Other parameters have been removed by suitable definitions of quark phases.) The unitarity of the matrix is expressed
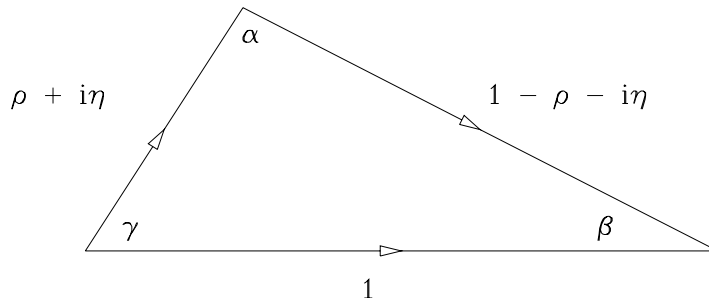
Figure 1: Unitarity triangle for CKM elements. The sides of the triangle are related to CKM elements through $\rho + i\eta \simeq -V_{ud}V_{ub}^*/V_{cd}V_{cb}^*$ and $1 - \rho - i\eta \simeq -V_{td}V_{tb}^*/V_{cd}V_{cb}^*$. From the diagram we see that the phase of V_{ub} is $-\gamma$ and that of V_{td} is $-\beta$.

in relations such as $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$, illustrated in terms of the triangle in Fig. 1. With these standard conventions, to a good approximation the only elements of the CKM matrix with non-zero phases are the smallest elements, V_{td} and V_{ub}, whose phases are $-\beta$ and $-\gamma$, respectively. Only transitions between the first and third generations introduce non-zero phases.

The CKM description of B decays may well be incomplete. If there are heavier generations of quarks and leptons, the b quark is the most likely particle to couple to them. Bosons beyond the usual W and Z may also participate in their decays, appearing virtually in loop diagrams. One particularly interesting example of this is the Higgs boson, which would appear with greater strength in the decays of the b quark than in those of the lighter quarks. The presence of these new phenomena would announce themselves by shifting the rates or phases of b-quark decays from our naive expectations.

3.1.3 CP violation.

The original weak interaction theory of 1957 involved maximal violation of parity (P) and charge-conjugation (C) invariance, but preserved the product CP as well as time reversal (T) invariance. Experiments in 1964 [**?**] showed that CP was violated as well. At present we believe both CP and T are violated, while the product CPT remains an experimentally valid (and theoretically welcome) symmetry.

The leading explanation of CP and T violation [**?**] involves the phases of

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the CKM matrix. A non-zero area of this *unitarity triangle* (i.e., a non-zero value of η) is a key feature of Kobayashi and Maskawa's explanation of CP violation in the neutral K meson (kaon) system.

All present knowledge about neutral kaon CP violation can be encoded in a single complex parameter ϵ, $\text{Arg}(\epsilon) \simeq \pi/4$, $|\epsilon| = (2.28 \pm 0.02) \times 10^{-3}$, with short- and long-lived kaons K_S and K_L related to states $K_{1,2} = (K^0 \pm \bar{K}^0)/\sqrt{2}$, even and odd under CP, by $K_S \simeq K_1 + \epsilon K_2$ and $K_L \simeq K_2 + \epsilon K_1$. In the KM theory ϵ is due to a second-order weak transition between K^0 and $\bar{K}^0$ involving intermediate states of $W^\pm$ and u, c, t. However, another viable possibility remains a "superweak" [?] direct first-order CP-violating mixing between K^0 and $\bar{K}^0$. The superweak theory will be tested in the next year or two through the comparison of K_S and K_L decays to pairs of charged and neutral pions. Disproof of the superweak theory in this experiment would be far from confirmation of the KM theory, however. With the discovery of the b quark in 1977, a whole new window of opportunity for studying the KM theory and its role in CP violation has opened.

While tests of the KM theory in decays of neutral kaons require very precise measurements or the study of very rare decays (as will be noted below), the anticipated CP-violating asymmetries in certain B-meson decays can reach tens of percent, once the required production rates have been attained. Furthermore, the wide variety of phenomena in B-meson decays (including many useful modes, B^0–$\bar{B}^0$ and B_s^0–$\bar{B}_s^0$ mixing, and lifetime differences among species) offers the chance to provide a definitive test of the KM theory or to expose inconsistencies that point to new physics.

3.2 Systematic study of B particles and decays

3.2.1 Improved knowledge of magnitudes of CKM matrix elements.

Our present knowledge of CKM parameters λ, A, ρ, and η comes from strange particle decays (λ), decays of b quarks to charmed (A) and charmless $([\rho^2 + \eta^2]^{1/2})$ final states, B^0–$\bar{B}^0$ and B_s^0–$\bar{B}_s^0$ mixing $(|1 - \rho - i\eta|)$ and CP violation in neutral kaons (approximately $\eta[1.4 - \rho]$), as shown in Fig. 2. In brief, $\lambda \simeq 0.22$, $A \simeq 0.8$, while a large region in (ρ, η) centered around $\rho \simeq 0.05, \eta \simeq 0.35$ is allowed. This corresponds to a rather restricted value of the angle β as defined in Fig. 1: $9° \leq \beta \leq 27°$, but the angles α and

γ are much less well known.

The evidence that $\eta \neq 0$ (hence, that not all weak coupling constants are real) comes primarily from the parameter ϵ in CP-violating neutral kaon decays. It is of great importance to confirm that $\eta \neq 0$. As shown in Fig. 2, a combination of information on $|V_{ub}/V_{cb}| \simeq \lambda(\rho^2 + \eta^2)^{1/2}$ and $|V_{td}| \simeq A\lambda^3|1-\rho-i\eta|$ can in principle constrain the unitarity triangle to have non-zero area (and hence η to be non-zero). However, many uncertainties (primarily theoretical) plague the determinations illustrated in Fig. 2.

The bounds on $|V_{td}|$ from B^0–$\bar{B}^0$ mixing involve an unknown hadronic matrix element, which must be estimated theoretically. More reliable is an estimate of $|V_{td}/V_{ts}|$ based on comparing the splitting Δm_d between mass eigenstates of the B^0–$\bar{B}^0$ system with the corresponding parameter Δm_s of the B_s^0–$\bar{B}_s^0$ system. Present information on Δm_d and Δm_s limits the CKM parameters (ρ, η) to lie to the right of the dot-dashed line in Fig. 2. The corresponding allowed range for the parameter $x_s \equiv \tau(B_s)\Delta m_s$, where $\tau(B_s) \simeq 1.5$ ps is the B_s lifetime, is $16 \leq x_s \leq 64$ [?]. The observation of a definite value for Δm_s is a prime goal of B-meson research.

The bounds on $|V_{ub}/V_{cb}|$ are limited by our theoretical understanding of the semileptonic B decays to particles composed only of u and d quarks. We are optimistic that experiment will reduce these barriers with detailed studies of exclusive decays such as $B \rightarrow \pi\ell\nu_\ell$ in the next 5 years. Such studies promise to reduce the uncertainty in $|V_{ub}/V_{cb}|$ from the current 25% to 10% [?].

Further improvements in $|V_{cb}|$ would be highly welcome. The error in the (ρ, η) band associated with the CP-violating K^0–$\bar{K}^0$ mixing parameter ϵ (the region bounded by the dotted lines in Fig. 2) is dominated by the error on $|V_{cb}|$. Studies of B semileptonic decays hold the promise of halving the uncertainty in $|V_{cb}|$ from the current 8%. The measurement of $\Gamma(B \rightarrow \tau\nu)$ will specify $f_B|V_{ub}|$ and, when combined with information on Δm_d, which gives $f_B|V_{td}|$, will establish the ratio $|V_{ub}/V_{td}|$ [?].

What might this figure look like by 2003? A plausible extrapolation is shown in Figure 3. The assumptions behind this extrapolation are derived from the subsequent sections of the report.
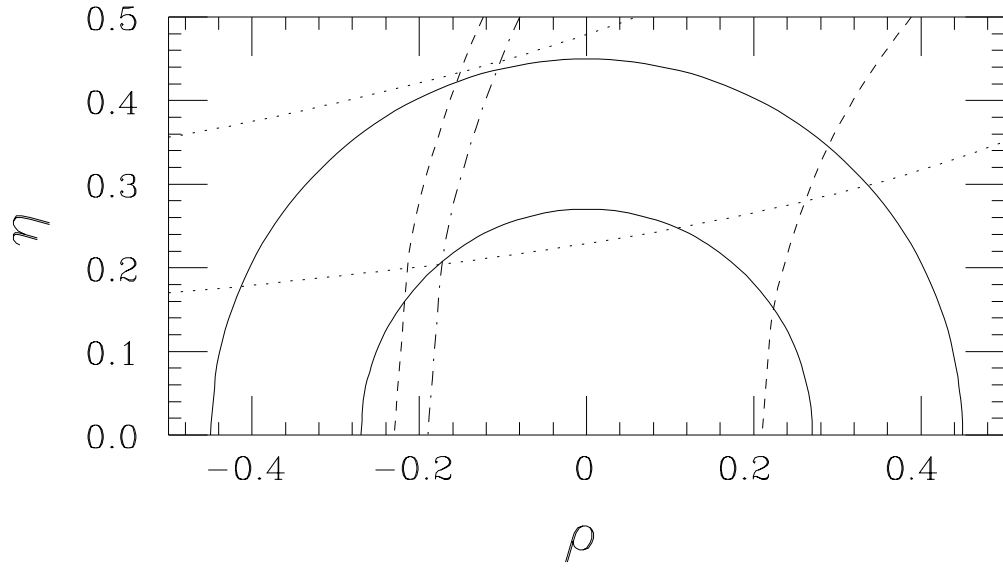
Figure 2: Regions in the (ρ, η) plane allowed by constraints on $|V_{ub}/V_{cb}|$ (solid semicircles), B^0–$\bar{B}^0$ mixing (dashed semicircles), CP-violating K–$\bar{K}$ mixing (dotted hyperbolae), and B_s^0–$\bar{B}_s^0$ mixing (to the right of the dot-dashed semicircle). Figure taken from Ref. [?].
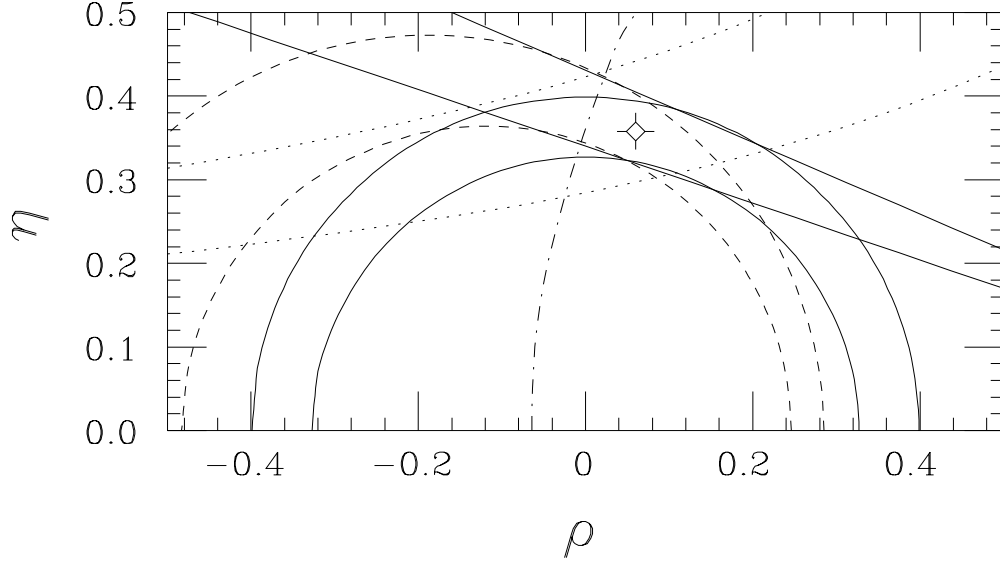
Figure 3: Example of a region in the (ρ, η) plane that might be allowed by data in the year 2003. Constraints are based on the following assumptions: $|V_{ub}/V_{cb}| = 0.08 \pm 0.008$ (solid semicircles), $|V_{ub}/V_{td}| = |(\rho - i\eta)/(1 - \rho - i\eta)| = 0.362 \pm 0.036$ based on present data on B^0–$\bar{B}^0$ mixing and a measurement of $B(B^+ \to \tau^+ \nu_\tau)$ to $\pm 20\%$ (dashed semicircles), CP-violating K–$\bar{K}$ mixing as in Figure 2 except with V_{cb} measured to $\pm 4\%$ (dotted hyperbolae), the bound $x_s > 20$ for B_s^0–$\bar{B}_s^0$ mixing (to the right of the dot-dashed semicircle), and measurement of $\sin 2\beta$ to ± 0.059 (see the first line of Table 9; diagonal straight lines). The plotted point, corresponding to $(\rho, \eta) = (0.06, 0.36)$, lies roughly within the center of the allowed region. The figure is drawn unrealistically assuming that every measurement will find as its central value the true value. What is important to notice is that the individual bands are narrow enough so that if the Standard Model is wrong or incomplete, inconsistencies could begin to be visible.

3.2.2 CP violation in decays to CP eigenstates.

According to our picture of weak quark decays, CP violation arises from the interference between two (or more) decay amplitudes with different weak phases. In general, the process $B^0 \to f$ interferes with $B^0 \to \bar{B}^0 \to f$. According to the KM model, the transition $B^0 \to \bar{B}^0$ in the second of these introduces a weak phase difference $-e^{2i\beta}$. If f is a CP eigenstate, then the amplitudes for $B^0 \to f$ and $\bar{B}^0 \to f$ are directly related.

In the especially attractive channel $B^0 \to J/\psi K_S$, the final state is CP odd and there is no phase introduced by the weak decay, so $\langle J/\psi K_S | \mathcal{H}_{\mathrm{wk}} | \bar{B}^0 \rangle = -\langle J/\psi K_S | \mathcal{H}_{\mathrm{wk}} | B^0 \rangle$. It follows that the time dependence is

$$\begin{aligned} \Gamma(t) &\propto& e^{-\Gamma t} |\cos \tfrac{1}{2}\Delta m_d t - i e^{-2i\beta} \sin \tfrac{1}{2}\Delta m_d t|^2 \\ &\propto& e^{-\Gamma t}[1 - \sin 2\beta \; \sin \Delta m_d t] \end{aligned} \tag{2}$$

For the decay of a state that is initially a $\bar{B}^0$, the sign of the $\sin \Delta m_d t$ term is reversed. Integrating over all times from $t = 0$ to $t = \infty$,

$$\begin{aligned} \Gamma(B^0 \to J/\psi K_S) &\propto& 1 - \frac{x_d}{1 + x_d^2} \sin 2\beta \\ \Gamma(\bar{B}^0 \to J/\psi K_S) &\propto& 1 + \frac{x_d}{1 + x_d^2} \sin 2\beta \end{aligned} \tag{3}$$

where $x_d = \Delta m_d / \Gamma \approx 0.7$. Thus we can obtain information on the unitarity triangle, without any ambiguity from strong interactions, by measuring the asymmetry

$$A(f) \equiv \frac{\Gamma(B^0 \to f) - \Gamma(\bar{B}^0 \to \bar{f})}{\Gamma(B^0 \to f) + \Gamma(\bar{B}^0 \to \bar{f})} = -\frac{x_d}{1 + x_d^2} \sin 2\beta \tag{4}$$

The dilution of the result by the ratio $x_d/(1 + x_d^2)$ is only a factor 0.47, close to the maximal value 0.5.

The decay $B^0 \to \pi^+ \pi^-$ is expected to be dominated by the "tree" process in which a $\bar{b}$ quark converts to a $\bar{u}$ quark, providing a phase $e^{i\gamma}$ from V_{ub}^*, with the opposite phase for $\bar{B}^0$ decay. Thus from this mechanism $\langle \pi^+ \pi^- | \mathcal{H}_{\mathrm{wk}} | \bar{B}^0 \rangle = e^{-2i\gamma} \langle \pi^+ \pi^- | \mathcal{H}_{\mathrm{wk}} | B^0 \rangle$ and for a state that is initially B^0,

$$\begin{aligned} \Gamma(t) &\propto& e^{-\Gamma t} |\cos \tfrac{1}{2}\Delta m_d t + i e^{-2i\beta - 2i\gamma} \sin \tfrac{1}{2}\Delta m_d t|^2 \\ &\propto& e^{-\Gamma t}[1 - \sin 2\alpha \; \sin \Delta m_d t] \end{aligned} \tag{5}$$

where we used the relation $\alpha + \beta + \gamma = \pi$. Unfortunately, this result, and the corresponding asymmetry, $A(\pi^+\pi^-) = -x_d \sin 2\alpha/(1+x_d^2)$, are not as reliable as those for $B \to J/\psi K_S$ because there is a second weak decay mechanism contributing to the $\pi\pi$ final state. This spoils the simple relation between the amplitudes for $B^0 \to \pi^+\pi^-$ and $\bar{B}^0 \to \pi^+\pi^-$.

How can we know that a state began as a B^0 rather than a $\bar{B}^0$? In the strong and electromagnetic interactions, b and $\bar{b}$ quarks are produced in pairs. If the same event contains a $B^- = b\bar{u}$ and a neutral B, the latter must have initially contained a $\bar{b}$ quark. Observing a charged B thus provides a tag for the opposing B. Inevitably, some of the inferred tags will be incorrect. The effective number of observed neutral B's is given by the total number, N, multiplied by ϵD^2, where ϵ is the combined efficiency for tagging together with reconstructing the neutral B. The dilution factor, D, is $1 - 2w$, where w is the fraction of incorrect tags.

In a hadron collider, mixing of neutral B's leads to an irreducible fraction of incorrect tags when tagging via associated $b\bar{b}$ production is used. The average probability that the B hadron used for the flavor tag mixes to a $\bar{B}$ hadron is $\chi_B = 0.118 \pm 0.006$, which results in a dilution factor of $D = 0.764 \pm 0.012$. This problem can be avoided by using a tagging technique based on the charge of a pion produced near the reconstructed B in phase space, but that technique has its own inefficiencies and chances for misidentification.

In e^+e^- colliders running at the $\Upsilon(4S)$ resonance, just above the threshold for $B\bar{B}$ production, tagging is more complicated. The decay of an $\Upsilon(4S)$ produces either B^+B^- or $B^0\bar{B}^0$. There is not enough energy to produce even a single additional pion. The B mesons are necessarily in a p-wave. Bose statistics guarantees that their flavors are coherent: If one meson is measured to be a B^0, then at that same instant the other must be $\bar{B}^0$. This coherence gives rise to a different time dependence and, in particular, if one neutral B is tagged and the other is observed decaying into a CP eigenstate, there is no asymmetry if the time interval between the tag and the CP-eigenstate observation is not measured. It is this obstacle that is overcome by asymmetric B factories. In an asymmetric machine the $\Upsilon(4S)$ is produced with substantial momentum and its decay products travel roughly 250 μm before decaying. Measuring the separation between the decay vertices of the two neutral B decays, and thus the time interval between the decays, provides the means to observe a CP asymmetry analogous to the one described above for hadron colliders. Once again, ϵD^2 provides a figure of merit for observing

CP violation.

The decay $B^0 \to J/\psi K_S$, probing $\sin 2\beta$, will likely be the first to yield a CP-violating asymmetry if standard-model predictions of $0.3 < \sin 2\beta < 0.8$ are correct. At the same time, there is room for $\sin 2\beta$ to lie outside this range. New physics can manifest itself in the box diagram responsible for B–$\bar{B}$ mixing, thereby altering the asymmetry in $B \to J/\psi K_S$, or indeed CP violation could arise from a mechanism outside the CKM matrix. The world sample of $J/\psi K_S$ events now exceeds several hundred, but the flavor of the accompanying B must be identified, leading to a significant dilution of the current effectiveness of CP-violation searches. Both e^+e^- and hadron collider experiments with stronger capabilities should begin useful studies of $\sin 2\beta$ within a year or two.

The decay $B^0 \to \pi^+\pi^-$, as mentioned, probes $\sin 2\alpha$, but "penguin processes" are likely to contribute at a level of tens of percent in amplitude. (A "penguin" amplitude denotes a transition of b to d or s via an intermediate state of a W and a charge 2/3 quark, with emission of one or more gluons or other gauge bosons.) Numerous suggestions have been made to resolve the effects of the two amplitudes, including the use of isospin relations [?] in conjunction with $\pi^\pm\pi^0$ and $\pi^0\pi^0$ or various $\rho\pi$ decay modes, or SU(3) relations in conjunction with various $K\pi$ modes [?]. At present the value of $\sin 2\alpha$ is very nearly unconstrained, so that a measurement of it would mainly serve to restrict the parameters (ρ, η) in Fig. 2.

Good tests of γ do not exist in decays to CP eigenstates. One proposed mode, $B_s \to \rho^0 K_S$, is expected to have a small branching ratio, requires a tagged B_s source, and should have a small asymmetry as a result of the smallness of the factor $x_s/(1 + x_s^2) < 0.06$. Several modes which do *not* involve decays to CP eigenstates may yield information on γ, as noted in the next subsection.

Although artificial, a "superweak" model can be constructed in which all CP violation in the B system would be due to B^0–$\bar{B}^0$ mixing, just as in the neutral kaon system (but requiring a much stronger mixing for B's than for K's). In this model, one would expect [?] $A(J/\psi K_S) = -A(\pi^+\pi^-)$ just as a result of the opposite CP of the $J/\psi K_S$ and $\pi^+\pi^-$ final states, a possibility that could be excluded by sufficiently precise measurements if (ρ, η) do not satisfy a relation equivalent to $\sin 2\beta = -\sin 2\alpha$.

3.2.3 Decays to states that are not CP eigenstates.

The difficulties mentioned above with regard to "tagging" the flavor of a produced neutral B meson when it decays to a CP eigenstate can be overcome by studying decays to "self-tagging" modes (which are necessarily not CP eigenstates). The final state f in such cases is either charged (signifying the charge of the $B^{\pm}$ which produced it) or has a flavor which can only have come from a neutral B of definite flavor (such as $K^+\pi^-$, which comes from a B^0 but very rarely from a $\bar{B}^0$). Unlike CP violation in decays to CP eigenstates, measurement of CP violation in these modes can be made at both symmetric and asymmetric e^+e^- colliders, and at hadron colliders, as well.

Any decay mode involving two real amplitudes A_i $(i = 1, 2)$ with weak phases ϕ_i and strong phases δ_i has rates

$$
\begin{aligned}
\Gamma(B \to f) &= |A_1 e^{i(\phi_1+\delta_1)} + A_2 e^{i(\phi_2+\delta_2)}|^2 \\
\Gamma(\bar{B} \to \bar{f}) &= |A_1 e^{i(-\phi_1+\delta_1)} + A_2 e^{i(-\phi_2+\delta_2)}|^2
\end{aligned} \tag{6}
$$

i.e., the weak phases change sign under CP, while the strong phases do not. The asymmetry is then

$$
A(f) = 2|A_1 A_2| \sin(\phi_1 - \phi_2) \sin(\delta_1 - \delta_2)/(|A_1|^2 + |A_2|^2), \tag{7}
$$

so that both strong and weak phases must differ in the two amplitudes in order that a CP-violating asymmetry be observable. Weak phase differences $\phi_1 - \phi_2$ can be anticipated theoretically, but only crude estimates exist at present for strong phase differences $\delta_1 - \delta_2$.

A number of predicted CP-violating rate asymmetries in charmless final states depend on interference between tree amplitudes $\bar{b} \to \bar{u}u\bar{d}$ or $\bar{b} \to \bar{u}u\bar{s}$ and penguin amplitudes $\bar{b} \to \bar{d}g$ or $\bar{b} \to \bar{s}g$. Relatively large rates appear to be associated with $\bar{b} \to \bar{s}g$ penguin amplitudes, as in the observed processes $B^0 \to K^+\pi^-$, $B^+ \to K^0\pi^+$, $B^{+,0} \to K^{+,0}\eta'$, and $B^+ \to K^+\omega$ [?]. (Here we do not distinguish between a process and its charge conjugate.) If the strength of the corresponding tree amplitudes can be established, there are prospects for observing a number of asymmetries in such processes, as well as others involving light pseudoscalar or vector mesons. These asymmetries depend on a favorable value of $\delta_1 - \delta_2$, making the experimental study of final state interactions in B decays of some urgency.

Independently of whether $\delta_1 - \delta_2 = 0$, there are numerous possibilities for learning the CKM phase γ and others by studying the rates for such processes. These include the study of the decays $B^+ \to \bar{D}^0 K^+$, $B^+ \to D^0 K^+$, $B^+ \to D^0_{CP} K^+$, and the charge-conjugate processes, where $D^0_{CP} \simeq (D^0 \pm \bar{D}^0)/\sqrt{2}$ are CP eigenstates [?]; the study of the time-dependence in the decays $B_s \to J/\psi K^*$ and $B_s \to D^\pm_s K^\mp$; and the comparison of the rates for various $B \to K\pi$ decays.

As one example [?], one can compare the rates for $B^+ \to K^0 \pi^+$ (expected to be overwhelmingly a penguin process) and $B^0 \to K^+ \pi^-$ (expected to have a small tree contribution as well as the dominant penguin amplitude). The ratio

$$R \equiv \frac{\Gamma(B^0 \to K^+ \pi^-) + \Gamma(\bar{B}^0 \to K^- \pi^+)}{\Gamma(B^+ \to K^0 \pi^+) + \Gamma(B^- \to \bar{K}^0 \pi^-)} \tag{8}$$

has the simple form

$$R = 1 - 2r \cos\gamma \cos\delta + r^2 \quad , \tag{9}$$

where r is the ratio of tree to penguin amplitudes in $B^0 \to K^+ \pi^-$, and δ is the difference of strong phases between these amplitudes. Fleischer and Mannel [?] have pointed out that if $R < 1$ a useful bound on γ can be obtained regardless of the value of r or δ:

$$\sin^2 \gamma \leq R \quad . \tag{10}$$

The present value of R is 0.65 ± 0.40, so a reduction of errors by a factor of three with no change in central value would begin to provide a useful limit excluding some region around $\gamma = \pi/2$. In the presence of information on r one can provide a more precise estimate of γ by measuring the difference in $B^0 \to K^+ \pi^-$ and $\bar{B}^0 \to K^- \pi^+$ decay rates. One forms the pseudo-asymmetry

$$A_0 \equiv \frac{\Gamma(B^0 \to K^+ \pi^-) - \Gamma(\bar{B}^0 \to K^- \pi^+)}{\Gamma(B^+ \to K^0 \pi^+) + \Gamma(B^- \to \bar{K}^0 \pi^-)} = 2r \sin\delta \sin\gamma \quad . \tag{11}$$

One can then combine (??) and (??) to eliminate δ. The result is

$$R = 1 + r^2 \pm \sqrt{4r^2 \cos^2\gamma - A_0^2 \cot^2\gamma} \quad . \tag{12}$$

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The ratio $r \simeq 0.2$ can be learned with adequate precision through the study of the decays $B^{\pm} \to \pi^{\pm}\pi^0$ or $B \to \pi\ell\nu_\ell$ decays using flavor-SU(3) symmetry and factorization. An estimate has been made [?] that one can learn γ to about $10°$ with a sample of about 3×10^8 B^+B^- pairs, or about 100 times the present e^+e^- sample. [Although what is actually measured in the above method is $\cos\gamma$ rather than γ, the two are approximately linearly related for $\gamma \simeq 90°$.] Such precision relies upon sufficient understanding of electroweak penguins and rescattering effects in order to exclude the possibility [?] of substantial uncertainties in γ, which could amount to tens of degrees. This underscores the importance of a wide variety of measurements to pinpoint electroweak penguin and rescattering effects experimentally.

At the moment there are typically one or at most two dozen events seen in many of the channels mentioned above, while the data for many others fall short by factors of typically two to five for definitive observation. The typical branching ratios for the observed channels are at a level of one to several times 10^{-5} [?]. Truly useful information can be expected to be gleaned from these processes when one can see the effects of smaller amplitudes (typically of order λ times the larger ones), requiring rates of order $1/\lambda^2 \simeq 20$ times those needed to see the dominant processes. Thus an overall improvement of present sensitivities by a factor of about $5 \times 20 = 100$, to the point where branching ratios of order 10^{-7} become observable, can pay large dividends in many channels, not only the example noted above.

In all of these processes, we are looking for phases differing from expectations based on our current picture of weak decays. An unexpected phase would signal the presence of a new decay mechanism involving processes or particles that will change our way of thinking about fundamental particles.

3.2.4 Rare decays involving loops.

New physics that affects the phases of weak decays, and therefore the CP-violating asymmetries may also affect decay rates. The gluonic penguin processes mentioned above involve loop diagrams. They are subject to contributions from virtual new particles in the loops. An example of a process that can be affected [?] is the decay $B^0 \to \phi K_S$, for which the standard model predicts the same asymmetry as for $B^0 \to J/\psi K_S$. This may not be the case if new physics contributes to the virtual $\bar{b} \to \bar{s}$ transition in $B^0 \to \phi K_S$.

A number of loop-dominated processes are summarized in Table **??**. One such process whose observed rate appears to be consistent with the standard model is $B \to X_s \gamma$, dominated by the $\bar{b} \to \bar{s}\gamma$ penguin diagram. The process $B \to X_s \ell^+ \ell^-$ would provide a different and more stringent test of the standard model, since many more types of loop diagram can contribute to it than to $B \to X_s \gamma$. Present experimental bounds are about a factor of eight above the standard model prediction.

Particles in loops that can affect gluonic and electromagnetic penguins and $B \to X_s \ell^+ \ell^-$ include supersymmetric partners of the known particles, new particles associated with dynamical electroweak symmetry breaking schemes, new quarks and leptons, or new Higgs bosons. These could well affect each of the above processes differently, and thorough studies of all modes would explore the nature of this new physics.

3.2.5 Dynamical questions.

In order to reap the full benefits of the studies of B decays, and translate measurements into underlying weak phases and amplitudes, we need to learn more about the dynamics underlying these decays. Interesting questions include the following:

- In processes like $B \to D^{(*)}\pi$, $D^{(*)}\rho$, $\pi\pi$, $\rho\pi$, …, where several isospin amplitudes contribute, one can form "isospin triangles" based on rates. Do these triangles have non-zero areas? The answers to this question for various processes can shed light on final-state phase shifts and/or weak phase differences.

- Are decays of B mesons to pairs of light vector mesons (as in $B \to J/\psi K^*$ or $B_s \to J/\psi \phi$) dominated by particular partial waves? The answers can help determine the mix of CP in final states in such processes as $B_s \to J/\psi \phi$.

- How important is rescattering? Such effects can lead to lifetime differences among species containing b quarks, to the appearance of unexpected enhancements in rates for otherwise very rare processes, and to significant strong phase shift differences that could enhance the prospects for observing CP-violating rate asymmetries.

Final State	Experimental limit or rate	Branching ratio in standard model [a]
$\mu^+\mu^-$	$< 8.6 \times 10^{-7}$ [b]	1.1×10^{-10} [c]
$\gamma\gamma$	$< 3.9 \times 10^{-5}$ [d]	10^{-8}
$X_s\gamma$	$(2.32 \pm 0.57 \pm 0.35) \times 10^{-4}$ [e] $(3.11 \pm 0.80 \pm 0.72) \times 10^{-4}$ [f]	$(3.25 \pm 0.30$ [g] $\pm 0.40) \times 10^{-4}$
$X_s\ell^+\ell^-$	$< 5.7 \times 10^{-5}$ [h] (ee) $< 5.8 \times 10^{-5}$ [h] $(\mu\mu)$	$(8.4 \pm 2.3) \times 10^{-6}$ (ee) $(5.7 \pm 1.2) \times 10^{-6}$ $(\mu\mu)$
$K^{*0}\gamma$	$(4.2 \pm 0.8 \pm 0.6) \times 10^{-5}$ [i]	$(4.0 \pm 2.0) \times 10^{-5}$
$K^{*0}\mu^+\mu^-$	$< 2.5 \times 10^{-5}$ [j] $< 4.1 \times 10^{-6}$ [k]	$(1.5 \pm 0.6) \times 10^{-6}$
$K^+\mu^+\mu^-$	$< 1.0 \times 10^{-5}$ [j] $< 5.4 \times 10^{-6}$ [k]	$(4.0 \pm 1.5) \times 10^{-7}$

[a] Ref. [?]. [b] CDF [?]. [c] Rate $\sim m_\ell^2$ for small lepton mass m_ℓ. [d] L3 [?].
[e] CLEO [?]. [f] ALEPH [?]. [g] Scale, m_t error. [h] CLEO [?].
[i] CLEO [?]. [j] CDF[?]. [k] CDF[?].

Table 2: Decays of nonstrange B mesons dominated by loop diagrams.

- Are penguin processes such as $\bar{b} \rightarrow \bar{s}g$ enhanced beyond standard expectations?

- Do the CP eigenstates of the B_s–$\bar{B}_s$ system have detectable lifetime differences? If so, there are numerous additional opportunities for studying CP violation in this system.

The answers to many of these questions are crucial if one is to distinguish signatures of new physics from imperfectly-understood effects of the strong interactions. Furthermore, such answers can help to convert qualitative evidence for CP violation (e.g., in decays to non-CP-eigenstates) into quantitative information bearing on the self-consistency of the KM description.

3.3 Related Physics Issues

3.3.1 Charm

Although the present report focuses on the b quark, many questions about the charmed quark can be addressed at the same time. Conventional estimates predict extremely small D^0–$\bar{D}^0$ mixing and small CP-violating asymmetries in charmed meson decays. These predictions remain to be tested definitively. The potential for uncovering effects of new physics is thus great, especially since charmed mesons are easier to produce in many cases (particularly in moderate-energy hadronic experiments) than B mesons.

3.3.2 Kaons

We have already mentioned a crucial test of the superweak theory involving comparison of K_L and K_S decays to pairs of neutral and charged pions. The parameter ϵ'/ϵ, a measure of direct CP violation, is probed in the double ratio

$$\frac{\Gamma(K_L \rightarrow \pi^0 \pi^0)}{\Gamma(K_S \rightarrow \pi^0 \pi^0)} \bigg/ \frac{\Gamma(K_L \rightarrow \pi^+ \pi^-)}{\Gamma(K_S \rightarrow \pi^+ \pi^-)} = 1 - 6 \, \mathrm{Re}\frac{\epsilon'}{\epsilon} \quad . \qquad (13)$$

In principle ϵ'/ϵ is proportional to η, though there are significant corrections due, for example, to electroweak penguins [?], and hadronic matrix elements are very uncertain. A likely range is $\mathrm{Re}(\epsilon'/\epsilon) = (0 - 10) \times 10^{-4}$ [?]. If $\epsilon'/\epsilon \neq 0$ the superweak theory [?] will finally have been disproved.

Several other experiments with kaons, either in progress or planned, can provide useful information on the CKM matrix. This information would provide a key check of the consistency of the standard picture when combined with that obtained from B mesons, and a valuable diagnostic tool if discrepancies are found.

1. The decay $K^+ \to \pi^+ \nu\bar{\nu}$ is sensitive to loop processes, mainly to V_{td}, but also to a non-negligible charm contribution. It roughly measures the parameter $|1.4 - \rho - i\eta|$. The standard prediction [?] is $\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu}) \simeq 10^{-10} \times 2^{\pm 1}$. Brookhaven Experiment E-787 has seen one event for this process [?], corresponding to a branching ratio of $(4.2^{+9.7}_{-3.5}) \times 10^{-10}$ or a limit $|1.4 - \rho - i\eta| > 0.7$. This does not yet encroach upon the allowed region in Fig. 2, but more data are expected.

2. The process $K_L \to \pi^0 e^+ e^-$ is dominated by direct and indirect ($\sim \epsilon$) CP-violating contributions; there is also a small CP-conserving two-photon contribution [?]. The direct contribution is proportional to $i\eta$; the indirect contribution is expected to have comparable magnitude and the phase of ϵ (about $\pi/4$). This process may be background limited before the expected branching ratio $[< \mathcal{O}(10^{-11})]$ is attained.

3. The process $K_L \to \pi^0 \nu\bar{\nu}$ is even more challenging, but can provide valuable information on η. The standard-model expectation for this branching ratio is $(2.8 \pm 1.7) \times 10^{-11}$ [?], more than 5 orders of magnitude below present upper limits [?].

3.3.3 Other searches for CP violation

1. Hyperon decays in principle can exhibit CP violation at expected levels of a few times 10^{-5}; a search for these effects is under way at Fermilab in $\Xi^- \to \Lambda\pi^-$, $\Lambda \to p\pi^-$ and its charge conjugate [?].

2. Electric dipole moments of the neutron and other particles are expected to be very small (far below present bounds) in the KM theory of CP violation, but can be close to present bounds in other theories. Improvements of present limits by two orders of magnitude (for the neutron) are foreseen in coming years [?].

3.3.4 Baryogenesis

The apparent preponderance of matter over antimatter in the Universe is a key manifestation of CP violation. The KM picture has great difficulty in accounting for this "baryon asymmetry of the Universe." One must either invoke some new feature of physics at the TeV scale (such as supersymmetry) or imagine that both the CKM phases and the baryon asymmetry of the Universe are low-energy manifestations of a unified theory of CP violation at some much higher mass scale.

A program of extensive studies of B physics can help choose between these two alternatives (or suggest others). If baryogenesis is primarily a TeV-scale phenomenon, driven mainly by CKM phases through the intermediary of new physics, a number of standard-model predictions for B physics (particularly those associated with mixing) are likely to be altered.

3.4 Stages of B Physics

We can divide experiments on B physics into three stages: completed experiments (Stage I), those in progress or approved (Stage II), and those that have not yet been approved but are proposed (Stage III).

3.4.1 Completed experiments ("Stage I").

We summarize in Table **??** some milestones in past studies of the b quark. Particular surprises included the small value of $V_{cb} \simeq 0.04$ (in comparison with the Cabibbo parameter $V_{us} = \lambda \simeq 0.22$), and the large value of the B^0–$\bar{B}^0$ mixing parameter $x_d \simeq 0.7$ indicating a very heavy top quark (as later confirmed). The pattern has so far been remarkably suitable for the KM explanation of CP violation in the neutral kaon system.

3.4.2 Experiments in progress or approved ("Stage II").

We summarize in Table **??** experiments that are to study B physics over the next few years. Many of these experiments are devoted to the first measurement of $\sin 2\beta$. Particularly sensitive experiments will also begin to provide information on $\sin 2\alpha$, but this will require the study of many final states (not just $\pi\pi$) and may take several years and gradual improvements in luminosity or detection efficiency.

Year	Experiment	Results
1977	Fermilab E288	Discovery of b quark
1977 −1978	Fermilab E288, ARGUS	Υ spectroscopy
1979-80	CLEO, CUSB	$\Upsilon(4S)$; discovery of B mesons
1983	MAC, MARK II	First measurement of V_{cb}
1986	UA1	Evidence for mixing
1987	ARGUS	Discovery of B_d^0–$\bar{B}_d^0$ mixing
1990	CLEO, ARGUS	First observation of $V_{ub} \neq 0$
1992-4	ALEPH, DELPHI, OPAL, CDF	B^0, B^+, B_s, Λ_b lifetimes
1993	ALEPH	Direct observation of time-dependence of B_d^0–$\bar{B}_d^0$ mixing
1993	CLEO	Observation of the penguin decay $B \to K^* \gamma$
1993	CDF, ALEPH	Full reconstruction of B_s
1994	CLEO	Precision measurement of $|V_{cb}|$
1996	ALEPH, DELPHI	Full reconstruction of Λ_b and precise mass measurement
1996	CLEO	Observation of exclusive $b \to u$ decays
1997	LEP	$x_s > 16$
1998	CDF	Evidence for B_c

Table 3: Milestones in the study of the b quark ("Stage I" experiments).

Experiment	Primary Goals in B Physics	Running begins
HERA-B	$\sin 2\beta$	1999
BaBar, BELLE	$\sin 2\beta$, α, γ, $|V_{ub}|$, $|V_{cb}|$, $|V_{td}|$, rare decays	1999 1999
CDF, D0 (Run II)	$\sin 2\beta$, $B \to \pi^+\pi^-$ asymmetry B_s–$\bar{B}_s$ mixing, rare decays	2000
CLEO-III	γ, rare decays, $|V_{ub}|$, $|V_{cb}|$, $|V_{td}|$	1999

Table 4: Experiments in progress or approved ("Stage II") for the study of the b quark.

The observation of $\sin 2\beta$ within the predicted range of 0.3 to 0.8 would be a key confirmation of the KM theory of CP violation, perhaps the first to emerge outside the realm of neutral kaon physics. A measurement of $\sin 2\alpha$, as mentioned earlier, is likely mainly to restrict the allowed range of parameters in Fig. 2, unless preceded by some other constraint. Improved measurements of the magnitudes of the CKM matrix elements can provide such constraints. Stage II experiments at e^+e^- colliders will reduce the uncertainty in $|V_{ub}|$ by about a factor of two. Some information on $|V_{td}/V_{ub}|$ could come from $B \to \tau\nu_\tau$. Initial information on γ should come from both the symmetric and asymmetric e^+e^- colliders. Nonetheless, it is probable that altogether these measurements would not provide a stringent test of the CKM model of weak interactions. Rare decays like $B \to K^*\mu^+\mu^-$ should be observed in both e^+e^- and hadron colliders, but their detailed study would likely not be possible, and the inclusive decay $b \to s\ell\ell$ would probably remain out of reach.

3.4.3 Potential experiments ("Stage III").

We summarize in Table 5 the future B physics experiments considered by the present panel. At present, three approaches are being considered: symmetric e^+e^- collider, asymmetric e^+e^- collider, and forward-geometry detectors at hadron colliders. Electron-positron colliders have a relatively large signal-

Type of experiment	Example(s)	Unique physics
Symmetric e^+e^- collider at $\mathcal{L} = 3 \times 10^{34}$ cm^{-2} s^{-1}	CESR Phase IV	Final states involving neutrals
Asymmetric e^+e^- collider at $\mathcal{L} = 3 \times 10^{34}$ cm^{-2} s^{-1}	Upgraded PEP-II or KEK-B	Final states involving neutrals, time-dependence
Hadron collider	BTeV, LHC-b	High rate B_s, Λ_b, B_c Time dependence for B_d, B_s Rare decays

Table 5: Potential ("Stage III") experiments in B physics

to-background ratio for b studies, but are rate-limited. They have excellent potential for neutral particle detection, as CLEO has ably demonstrated. Hadron colliders produce many more b's but face the challenge of isolating signal from a much more copious background. They permit the study of a much broader range of hadrons containing b quarks than e^+e^- machines operating on the $\Upsilon(4S)$. However, neutral particle detection in hadron colliders appears a formidable task.

Stage III would provide the statistics needed to make the tests begun in Stage II rigorous. A more thorough discussion of the particular advantages of each type of experiment is the subject of the next two sections.

4   Experimental Approaches to B Physics

4.1   Facilities for Studying B Physics

In this section, we discuss the strengths and weaknesses of e^+e^- and hadron machines, summarize the b rates at each, and conclude with our best estimate of what physics is accessible to them.

The program of measurements described above requires a copious source of hadrons containing b quarks. A rule of thumb for the uncertainty in $\sin 2\beta$ determined as the coefficient of the $\sin \Delta mt$ term in the time-dependent decay rate is $\sigma = \sqrt{3/N_{\text{perfect}}}$, where N_{perfect} is the number of reconstructed, tagged events. Thus a sample with $N_{\text{perfect}} = 100$ gives $\sigma = 0.17$, a reasonably

good measurement. For the important mode $B^0 \to J/\psi(\mu^+\mu^-)K_S(\pi^+\pi^-)$ the branching fraction is about 1.8×10^{-5}. With the optimistic estimate that half the $B^0 \to J/\psi(\mu^+\mu^-)K_S(\pi^+\pi^-)$ events would be reconstructed and tagged, we see that a sample of about 10^7 would be required for this measurement, ignoring any problems introduced by backgrounds.

For $B^0 \to \pi^+\pi^-$, CLEO has an estimate [?] that the branching fraction is $\sim 0.7 \times 10^{-5}$ [?]. Thus rather more B's will be required to study this channel. Such large samples would also allow precision measurements of the magnitudes of the CKM matrix elements V_{ub} and V_{cb}, determination of the B-meson decay constant, and thereby the magnitude of V_{td} (with a precision of 12%) and a first determination of the weak angle γ.

Much larger samples of B's, more than 10^8 per year, are required to observe direct CP violation, to make a good measurement the weak phase γ, to search for new physics in $b \to s\ell\ell$ and other rare decays, or to obtain higher precision in the measurements of sin2β. Such measurements are the domain of the Stage III experiments.

Two general classes of machines can produce b-hadrons at the required rate and each class has variations. These are

- electron-positron colliders, including

  - symmetric energy machines running near $B\bar{B}$ threshold;
  - asymmetric energy machines running near $B\bar{B}$ threshold; and
  - machines running at the Z^0, well above $B\bar{B}$ threshold.

- machines that can produce hadron-hadron collisions, including

  - fixed target facilities (high energy beams interacting in solid targets); and
  - hadron-hadron colliding beam/storage ring facilities.

4.1.1 Electron-positron colliders at the Υ(4S)

The Υ(4S) resonance, with mass 10.58 MeV [?], is the lowest lying $b\bar{b}$ resonance accessible to e^+e^- colliders that has sufficient mass to decay into pairs of B mesons, B^+B^- and $B^0\bar{B}^0$. Physics at the Υ(4S) is clean experimentally. In the Υ(4S) rest frame, the B mesons are nearly at rest, allowing stringent

constraints on their decay products. Events consist of the $B\bar{B}$ pair with no attendant particles, allowing high reconstruction and tagging efficiencies. The most important background, from continuum processes, is relatively low (about three times the signal), is separable from $B\bar{B}$ events by applying event topology cuts, and is measurable by collecting data off-resonance. Rates in the detectors are relatively modest. This clean environment and the low momenta of the B's permit clean reconstruction of π^0's produced in B decays. The narrow range of momenta of K's and π's simplifies devices aimed at distinguishing them.

The $B\bar{B}$ production cross section at the $\Upsilon(4S)$ is 1.15 nb [**?**], so the Stage II goals require luminosities of a few 10^{33}cm^{-2}s^{-1}. At present, the highest luminosity e^+e^- collider, CESR, has achieved over 5×10^{32}cm^{-2}s^{-1}. The e^+e^- 'B factories' that will run in the next five years are designed to achieve luminosities of 1.7×10^{33}cm^{-2}s^{-1} for CESR III and 3×10^{33}cm^{-2}s^{-1} for PEP-II and the KEK machine. Possibilities for achieving much higher luminosity, 3×10^{34}cm^{-2}s^{-1}, are now under investigation at CESR and PEP-II.

Symmetric vs Asymmetric e^+e^- colliders

All e^+e^- machines to date have been 'symmetric' machines – that is, two beams of equal energy have collided head-on. On the $\Upsilon(4S)$, because in the initial state the B^0–$\bar{B}^0$ system is in a p-wave, time-integrated asymmetries from mixing-induced CP violation vanish. To observe mixing-induced CP violation one must study the time evolution of the B decays. This is impossible in a symmetric machine running on the $\Upsilon(4S)$ where the produced B's have $\beta = 0.06$ and travel an average of $\beta\gamma c\tau = 26$ μm before decaying. This is too short to be measured reliably with the kinds of microvertex tracking devices we currently know how to build. This problem is overcome with an 'asymmetric' e^+e^- collider – a machine with two storage rings of unequal energies that give a center of mass energy equal to the $\Upsilon(4S)$. The PEP-II machine at SLAC has two rings which, when tuned to the 4S, operate at energies of 9 GeV and 3.1 GeV. The center of mass moves in the lab and the B's are boosted to $\beta\gamma = 0.56$. With this arrangement of energies, the B's separate of order 250 μm before they decay. One can study the time evolution with conventional silicon vertex technology and observe mixing-induced CP asymmetries. Such machines can be 'tuned' over a limited range to other resonances such as the $\Upsilon(5S)$, which is above the threshold for production of $B_s\bar{B}_s$ pairs.

The main strength of the asymmetric energy machines is the ability to study the time dependence of B decays. However, the separation of decay vertices may also reduce the chance of associating two tracks from different particles, which is a source of background. This also reduces the running time that has to be devoted to running 'off resonance' to study the background. These effects seem to be small for clean modes, and worth about a factor of two in effective yield in circumstances where reconstruction is most difficult. On the other hand, the high energy ring in a asymmetric machine produces a good deal of synchrotron radiation, which must be absorbed before it reaches the detector and in general the interaction region is more complicated. Because of the boosted center of mass, the occupancy of the detector is peaked towards the direction of the more energetic beam, possibly affecting reconstruction efficiency there.

At this time, we do not know whether any unforeseen obstacles will make it hard to achieve the luminosity goals at the asymmetric machines. Much will be learned from the startup and the first few years of operation of these machines. Another uncertainty is whether machine backgrounds will cause problems in asymmetric machines. The machine background at CESR is low and well-understood.

Electron-positron colliders and B_s physics

The $\Upsilon(4S)$ is below threshold for decay into $B_s \bar{B}_s$ pairs. In order to study B_s decays, e^+e^- machines must operate at the $\Upsilon(5S)$, whose mass is 10.868 MeV [?, ?]. Although this resonance has been observed, its properties are poorly known. It is believed, however, that the B_s production rate is too small to permit measurement of Δm_s or to observe CP violation in B_s decay. The $\Upsilon(5S)$ cross section at the peak is small, about 0.3 nb or less [?, ?] , and is shared among six final states, $B\bar{B}, B\bar{B}^* + B^*\bar{B}, B^*\bar{B}^*, B_s\bar{B}_s, B_s\bar{B}_s^* + B_s^*\bar{B}_s$, and $B_s^*\bar{B}_s^*$. These facts, combined with the phase space preference for the lighter B_d modes [?], lead to expectations for $B_s\bar{B}_s$ production of rather less than 0.1 nb. In addition to the low production rate, studies of the B_s at the $\Upsilon(5S)$ would suffer from backgrounds from B_d and B_u. (The production of $B(B^*)$'s with a pion is an additional complication.)

It will require luminosities of at least $3 \times 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ to make B_s physics at e^+e^- machines possible. Even at asymmetric machines, however, the relatively small boost (compared to hadron machines) makes it difficult to detect B_s mixing if the mixing parameter x_s is significantly over 10, as indicated

by results from LEP. Finally, we note that running at the $\Upsilon(5S)$ requires a sacrifice in B_d physics, which is much better done at the $\Upsilon(4S)$ resonance.

4.1.2 e^+e^- colliders running at the Z^0

An e^+e^- collider tuned to the peak of the Z^0 is also a source of b hadrons. The b-pair cross section is about 6.7 nb [?], several times that at the $\Upsilon(4S)$. The b hadrons have a very high boost, so time evolution of B's can be observed. Two such machines exist – LEP at CERN and the SLC at SLAC. They produce all species of b hadrons and have been a source of information on B^0, B^+, B_s and b-baryon decays and lifetimes, mixing, and excited B mesons. LEP has been a leader in measuring b-hadron lifetimes and in observing the time-dependent mixing of the B_d. However, for a variety of technical reasons, the LEP machine only achieves a luminosity of a few 10^{31}cm^{-2}s^{-1} and SLC is somewhat lower. Neither machine produces enough b hadrons to achieve high sensitivity to CP violation in B decays. Both machines have, however, the capability of measuring Δm_s quite well. Recent results from LEP indicate $x_s > 16$. With the 350,000 events SLD should have by the end of its 1998 run, it hopes to measure the mass difference Δm_s if it is less than 14 ps^{-1}, that is, up to x_s of about 20.

4.1.3 Hadron machines

The B cross section in hadron-hadron collisions is a strong function of center of mass energy. In collisions of $\sim$900 GeV protons with a fixed target, which can be produced at HERA in the HERA-B experiment or at Fermilab, the cross section is of order 10 nb. At Tevatron collider energies, 2 TeV in the center of mass, the cross section is of order 100 μb. At LHC energies, 14 TeV in the center of mass, the cross section is predicted to be about 500 μb. Given the available luminosities, these colliders produce prodigious numbers of b hadrons. For example, the Tevatron, operating at a luminosity of 10^{32}, produces 10^{11} b pairs per year. Moreover, hadron machines simultaneously produce all species of B's: B_d, B_u, B_s, b baryons of all sorts, and B_c states.

The kinematics and dynamics of B production in hadron interactions have characteristics that are important for studying B decays. Since the $b\bar{b}$ pairs are formed in the collision of a parton, usually a gluon, from each beam particle, the collisions are intrinsically asymmetric. For the B hadrons, this

results in a relatively flat distribution in rapidity and a mean P_t of about 5 GeV/c which is almost independent of the rapidity. When the asymmetry is not too large, the B's are produced in the central region with relatively low momenta and the daughter products of the decays have momenta that are typically between 100 MeV/c and a few GeV/c. When the collisions are more asymmetric, both B's are boosted in the same direction (either both forward or both backward in the lab) and the daughter products of the decays cover a wide range of momenta, typically from a few GeV/c to many tens of GeV/c. In either case, the B's travel far enough before they decay so that the decay vertices can be separated from the interaction vertex. The B and $\bar{B}$ are also correlated in angle. This correlation means that in either a central detector or a forward detector, if one B is accepted and reconstructed, the other B may also be within the acceptance and its daughters can be used for flavor tagging. A wide variety of tagging strategies can be employed in both the forward and central regions. CDF has already achieved a combined effective efficiency of 2.7% and future experiments, both forward and central, expect to achieve ϵD^2, of order 10%.

The main difference between the central region and the forward region in hadron collisions is the momenta of the decay products of the B hadrons. This results in very different considerations in designing the vertex detector and charged particle identification system. Proposed forward experiments are able to place the vertex detector closer to the interaction region than existing or proposed central detectors, and this, combined with lower multiple scattering due to the higher momenta of the tracks, results in better vertex and proper time resolution. For example, the BTeV spectrometer expects to achieve a proper time resolution of 35-50 fs depending on the final state while the CDF Run II detector expects to achieve about 100 fs. Most central detectors have only limited charged hadron identification and are severely constrained in the space available to add capability. Forward detectors all have provision for Ring Imaging Cerenkov detectors which give them excellent charged hadron identification from a few GeV/c to close to 100 GeV/c.

With these advantages come some serious challenges. The B-hadron cross section is only a small part of the total cross section so B events are accompanied by a very high rate of background events. Only one event in about a thousand at the Tevatron has a B pair. The B's are also produced over a very large range of momenta and angles. Even in the B events of interest there is a complicated underlying event, so one does not have the stringent

kinematic constraints that one has at an e^+e^- machine and that aid in tagging and background rejection. These conditions create problems that result in lower efficiency than is attainable at e^+e^- machines, and restricts analyses to modes with charged final-state particles.

4.1.4   Comparison of e^+e^- and hadron-hadron colliders

Hadron colliders and e^+e^- colliders face very similar tasks in doing B physics. The trigger must identify candidate events that might contain B's. Backgrounds from various sources must be rejected. The charged particle tracks must be reconstructed and the π^0's and γ's identified from an electromagnetic calorimeter. Particle identification for charged leptons and hadrons is necessary to isolate exclusive decays. Time-dependent studies demand extremely good tracking resolution. Studies of CP violation due to mixing require tagging of a B meson that is not completely reconstructed, a task that relies, in part, on particle identification.

These tasks lead to very different challenges in the e^+e^- and hadron colliders. At a hadron collider, b-hadron events account for about 0.1% of the total cross section, so the main issues are triggering, tagging, reconstruction efficiency, and background rejection. In order to deal with these issues, hadronic B experiments must employ state-of-the-art vertex detectors, triggering systems, and data acquisition systems. While these are concerns at an e^+e^- collider as well, there is a big advantage in having 25% of the events contain B's. The e^+e^- experiments are also concerned with reconstruction efficiency and background suppression, but for them the biggest issue is producing enough B mesons to reach the interesting physics: Accelerator luminosity is pivotal.

A powerful microvertex detector is necessary to measure the time distribution of decays to study mixing-induced CP violation and B_s mixing. At e^+e^- machines it is also useful for background suppression. At hadron colliders it is a *sine qua non* for a broad program of B-physics studies because it enables one to distinguish B-meson events from light quark events on the basis of the displaced B-decay vertex. Furthermore, the vertex detector helps reject combinations of tracks in which some come from each B decay – a significant source of background. One may push this further and require that track combinations 'point back' to the primary interaction point. At e^+e^- machines, the vertex detector will be used in the same ways, particular-

ly at the asymmetric machines, but, because the backgrounds are less, with mitigated urgency. In both the hadron and e^+e^-environments, low-mass, radiation-hard detectors and electronics are essential. In hadron colliders, the vertex detector has the added burden of fighting enormous backgrounds and surviving the high particle flux near the interaction point.

Charged particle identification is also important at both e^+e^-colliders and hadron colliders. Some form of Cerenkov detection is the universal solution, with the radiator being gas, quartz, or aerogel. At an e^+e^-collider, the range of momentum over which particle identification must function is rather small, extending to just 2.6 GeV at symmetric and 4.5 GeV at asymmetric machines for the crucial separation of π/K in $B \to \pi\pi$ vs. $B \to K\pi$. Hadron collider detectors with a forward geometry need particle identification over a large range of momenta – typically from a few GeV to close to 100 GeV. Gas ring imaging Cerenkov detectors can meet this challenge. In the central region, the hadron spectrum is concentrated at lower momenta and is more similar to that encountered in e^+e^-collisions.

Muon and electron identification are important for final states containing leptons and for tagging. Electron identification relies on electromagnetic calorimetry in both types of experiment. Some experiments supplement the calorimeter with information on specific ionization from tracking chambers. Muon identification uses conventional technology at both e^+e^-colliders and hadron colliders.

At e^+e^-colliders, π^0's are reconstructed with excellent resolution and efficiency in CsI electromagnetic calorimeters. Neither of the proposed forward B experiments at hadron colliders has explored π^0 reconstruction in detail, however it appears that the large combinatoric backgrounds may make it impossible to reconstruct final states containing a γ, π^0 or η. The combinatoric problem is exacerbated by the lack of directional information from the calorimeter, which prevents association of these neutral particles with a particular decay vertex.

In rare decays, e^+e^-experiments will probably be alone in isolating inclusive rare decays, such as $X_s l^+ l^-$, where they will benefit from knowing the the B energy. They will also be alone in searches for final states including one or more γ, π^0 or η. Hadron experiments will reap the benefits of their large B production rate for exclusive rare decays containing only charged particles, and should do better for these modes.

For the hadron experiments, triggering is a central challenge. The inter-

action rate is of order 10 MHz, so even if a rate of data to archival storage of 1 kHz is allowed, the trigger must reduce the rate by a factor of more than 10,000. Triggers based on high-momentum muons have proved successful at CDF; access to a broader range of B physics requires a less restrictive trigger. Most hadron collider experiments now envision triggering on a high-P_T hadron or displaced vertex, or both. Construction of such triggers is one of the main challenges facing the forward hadron experiments. At e^+e^-machines, triggering and data acquisition needs are relatively modest: The multiplicity and large energy deposited by hadronic events (including B events) distinguish them from other event types, and even with a luminosity of 3×10^{34}cm^{-2}s^{-1} the hadronic event rate is a modest 120 Hz. Beam gas and other beam background events tend to have low multiplicity, and present triggering problems primarily for low-multiplicity physics such as τ or two-photon rather than for B physics.

Hadron experiments will record much more data than e^+e^- experiments and will need much more CPU and data storage.

Fixed target experiments such as HERA-B operate at much lower center of mass energies than hadron collider experiments. At the HERA-B energy, the B cross section is 10,000 times smaller than at the Tevatron and accounts for only 10^{-6} of the total cross section, making all of the problems cited above for hadron colliders worse. However, HERA is the only facility that will be running around the year 2000 that has already demonstrated that it can achieve the luminosity required to study CP violation (with the possible exception of CDF and D0). If the detector achieves its design efficiency and rate capability then HERA-B may be the first experiment to observe CP violation in B decay.

While both $e^+e^-$and hadron collider experiments in B physics face a multitude of serious challenges, the most serious of these are simply stated:

- At e^+e^- machines: to achieve sufficient luminosity to produce the number of B mesons required for the study of CP violation and rare decays.

- At hadron machines: to trigger efficiently, reconstruct, and tag b hadrons.

In Table **??**, we list the luminosities, cross sections, and rates of B's produced at various present and future machines. In Table **??**, we list the comparative strengths and weaknesses of e^+e^- colliders and hadron-hadron

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colliders for various physics topics. The judgments, of course, are those of the committee and represent our best understanding of the subject at this time. The table supports the conclusion that it will take experiments at both e^+e^- machines and hadron colliders to carry out the full program of study of CP violation in B decays.

Facility	$\mathcal{L}$	$\sigma(B\bar{B})$	$\int \mathcal{L}dt$	$B\bar{B}$ pairs
Present facilities:				
(Stage I)				
CESR II e^+e^- $\Upsilon(4S)$	5×10^{32}	1.15 nb	9.5	5×10^6
LEP e^+e^- Z^0	1.6×10^{31}	6.7 nb	0.16	0.9×10^6
FNAL Run I $(p\bar{p})$	2×10^{31}	100 μb	0.1	1×10^{10}
Next round facilities:				
(Stage II)				
PEPII e^+e^- $\Upsilon(4S)$	3×10^{33}	1.15 nb	30	3×10^7
also KEK				
PEPII e^+e^- $\Upsilon(5S)$	3×10^{33}	0.1 nb[a]	30	3×10^6
CLEO III e^+e^- $\Upsilon(4S)$	1.7×10^{33}	1.15 nb	17	2×10^7
CLEO III e^+e^- $\Upsilon(5S)$	1.7×10^{33}	0.1 nb[a]	17	2×10^6
FNAL Run II [b]$(p\bar{p})$	1×10^{32}	100 μb	1.0	1×10^{11}
HERA-B	40 MHz [c]	$\sim$10 nb	–	3×10^8
Facilities after 2003:				
(Stage III)				
BTeV FNAL $(p\bar{p})$	2.0×10^{32}	100 μb	2.0	2×10^{11}
Upgraded PEPII e^+e^-	3×10^{34}	1.15 nb	300	3×10^8
CESR Phase IV e^+e^-	3×10^{34}	1.15 nb	300	3×10^8
LHC [d] pp ($\geq$2005)	1.5×10^{32}	500 μb	1.5	8×10^{11}

[a] Estimated $B_s\bar{B}_s$ based on arguments like those outlined in the text.
[b] Main Injector Design. Upgrades have been proposed.
[c] Interaction rate per second on 50 μm diameter C, Cu, or Al target.
[d] LHC-B reference design.

Table 6: Luminosity goals, cross sections, and rates of produced B's. The luminosity $\mathcal{L}$ is given in cm^{-2}s^{-1}. The integrated luminosity, $\int \mathcal{L}dt$, is given in fb^{-1}. For Stage I, the value given is for the cumulative data analyzed thus far. The numbers for LEP are representative of a single experiment. For Stages II and III, it is the projected amount for one year's (10^7s) running. The number of $B\bar{B}$ pairs is for a year's running.

topic	Symmetric e^+e^- at the $\Upsilon(4S)$	Asymmetric e^+e^- at the $\Upsilon(4S)$	hadron collider
$\sin 2\beta$	−	+	+
α	?	+	+
Direct CP violation	+	+	+
γ	+	+	+
x_s	−	−	+
Absolute branching fractions B_d	+	+	−
Absolute branching fractions B_s	?	?	?
General properties of B_s decays	?	?	+
B_c physics	−	−	+
b-baryon physics	−	−	+
Rare exclusive $B_{u,d}$ decays with γ's	+	+	?
Rare exclusive $B_{u,d}$ decays with π^0's	+	+	?
Rare exclusive $B_{u,d}$ decays with l^+l^-	+	+	+
Rare inclusive $B_{u,d}$ decays with γ's	+	+	?
Rare inclusive $B_{u,d}$ decays with π^0's	+	+	−
Rare inclusive $B_{u,d}$ decays with l^+l^-	+	+	?
Very rare exclusive $B_{u,d}$ decays	−	−	?
Rare exclusive B_s decays with l^+l^-	−	−	+
Semileptonic decays $(B_{u,d} \to c)$	+	+	+
Semileptonic decays $(B_{u,d} \to u)$	+	+	?
Semileptonic decays $(B_s \to c)$	−	−	+
Semileptonic decays $(B_s \to u)$	−	−	?
Leptonic decays of $B_{u,d}$	+	+	−
Leptonic decays of D and D_s	+	+	−

Table 7: Strengths and weaknesses of machines for important physics topics. In the table, a + indicates belief that significant measurements can be made; − indicates that they cannot; and ? indicates that the capabilities are uncertain.

4.2 The Experiments

The committee heard reports from BaBar, CLEO, CDF, D0, and HERA-B, all of which will begin new studies in the period of 1998 and 2000. It did not hear from BELLE, an experiment at KEK with capabilities quite similar to those of BaBar. This round of experiments is expected to observe the first evidence for CP violation in B decays, make great strides in determining the magnitudes of the CKM matrix elements V_{ub}, V_{cb} and V_{td}, determine $\sin 2\beta$ well, α somewhat less well, and make first measurements of the CKM angle γ. We expect that after this round of experiments, many critical measurements will remain undone, both on the current list and on topics suggested by new experimental results or theoretical work done during this period.

In addition, the Panel heard from experiments that could run after the year 2003. The Panel heard presentations from both CESR and PEP-II about upgrading their machines to $3 \times 10^{34} \mathrm{cm}^{-2}\mathrm{s}^{-1}$. The Panel also heard about two 'dedicated hadron collider' B experiments – BTeV, at Fermilab, and LHCb, at the LHC. It did not review the capabilities of ATLAS and CMS in the area of B physics for reasons that will be addressed below. All of these experiments are aimed at completing the program of the first round and carrying it further. Emphasis will be on observation of direct CP violation, measurements of x_s (if it is large and has not already been measured), precision measurement of γ, precision measurements of α, studies of rare B decays involving loops, and studies of the dynamics of B decays.

4.2.1 Stage II: Experiments scheduled to run beginning in 1999-2000

BaBar

The BaBar detector will begin to take data at the SLAC PEP-II asymmetric energy e^+e^- collider in 1999. Its goal is to make detailed measurements of the sides and angles of the CKM triangle to ascertain whether the Standard Model explanation fully accounts for the observed pattern of CP violating effects. The particular strength of the asymmetric machine is that it permits a measurement of the time-ordered asymmetry due to mixing-induced CP violation. With a boost of $\beta\gamma = 0.56$, the B's separate enough before they decay to allow measurement of the time evolution with the silicon vertex tracker (SVT).

To carry out its proposed program, BaBar has, in addition to the SVT, a solenoid for momentum analysis, a drift chamber, a DIRC (Detection of Internally Reflected Cerenkov light) for charged-hadron identification, a cesium iodide calorimeter for reconstruction of electromagnetic showers, and a muon detector/neutral hadron identifier. Because of the unequal beam energies, the detector itself is asymmetric.

The program was described as developing in three phases:

- At the PEP-II design luminosity of $3 \times 10^{33} \mathrm{cm}^{-2}\mathrm{s}^{-1}$, BaBar will measure $\sin 2\beta$ and $\sin 2\alpha$, study many decays that test the theoretical assumptions connecting the experimental measurements to CKM parameters (for example, by establishing the penguin contribution in some of the mixing-induced CP violation measurements or by measuring strong phase shifts that figure prominently in 'direct' CP violating decays), improve the measurements of the sides of the unitarity triangle, and improve the sensitivity of searches for rare decays.

- In a subsequent upgrade of PEP-II to $10^{34} \mathrm{cm}^{-2}\mathrm{s}^{-1}$, BaBar will be able to begin the study, with modest accuracy, of γ.

- With a second upgrade of PEP-II to a luminosity of $3 \times 10^{34} \mathrm{cm}^{-2}\mathrm{s}^{-1}$, more precise measurements of γ will become possible, better measurements of many asymmetries will be carried out with good accuracy, and it will be possible to search for rare decays at the level of 1 part in 10^{7-8}.

If any precision work on B_s decays is undertaken, it will almost certainly occur in the highest luminosity phase.

BELLE

The BELLE detector will run at the KEK asymmetric e^+e^- collider slated to turn on in 1999. While the committee did not hear a report on the BELLE detector and program, its goals and expected luminosity are similar to those of BaBar.

CESR/CLEO . The Cornell Electron Storage Ring (CESR) and the CLEO detector were first commissioned in 1979. Since that time the facility has been a leader in B physics as well as in charm, tau and two-photon physics. Among CLEO's accomplishments are the discovery of the B meson (with

CUSB) and of the $b \rightarrow c$, $b \rightarrow u$ and $b \rightarrow s$ transitions. Over half of the entries in the Particle Data Listings for the B meson and for the charmed mesons and baryons are based primarily on CLEO results.

The performance of CESR has been a primary factor in CLEO's achievements. Many of the innovations pioneered at CESR are now in widespread use. These include bunch trains, pretzel orbits and superconducting RF techniques. CESR holds the world record luminosity of over $5 \times 10^{32} \mathrm{cm}^{-2}\mathrm{s}^{-1}$, and has delivered more than 11 fb^{-1} to CLEO.

The CLEO II detector features a CsI calorimeter (installed in 1990) and a three-layer double-sided silicon vertex detector (installed in 1995) as well as drift chambers inside a 1.5 T superconducting solenoid, a time-of-flight system, and a muon detector.

Among CLEO's recent accomplishments are

- Measurement of the CKM matrix element $|V_{cb}|$ via the exclusive decay $B \rightarrow D^* \ell \nu$ $[|V_{cb}| = (39.5 \pm 3.6) \times 10^{-3}]$ and via inclusive decays $b \rightarrow c\ell\nu$ $[|V_{cb}| = (39.6 \pm 1.4 \text{ (stat)}) \times 10^{-3}]$,

- Measurement of $|V_{ub}|$ by observing the endpoint of the lepton spectrum in $b \rightarrow u\ell\nu$, and using the exclusive decays $B \rightarrow \pi\ell\nu$ and $B \rightarrow \rho\ell\nu$,

- Measurement of B^0–$\bar{B}^0$ mixing. Important in its own right, this is a first step towards measuring $|V_{td}|$.

- Measurement of the inclusive rate for the radiative penguin process $b \rightarrow s\gamma$,

- Measurement of several two-body hadronic charmless B decays including $B^0 \rightarrow K^+\pi^-$, $B^+ \rightarrow \eta'K^+$, and $B^0 \rightarrow \eta'K^0$. There are indications for other $B \rightarrow K\pi$ decays and for $B \rightarrow \pi\pi$.

Major upgrades to CESR and CLEO will be installed in 1999. The CESR upgrade features superconducting RF cavities, strong focusing near the interaction point and an improved feedback system. With these additions, CESR accelerator physicists anticipate a peak luminosity in excess of $1.7 \times 10^{33} \mathrm{cm}^{-2}\mathrm{s}^{-1}$. The upgraded detector, called CLEO III, will include a new ring-imaging cerenkov counter (RICH) for charged-hadron identification, a four-layer silicon vertex detector, a new drift chamber, and an improved

trigger and data acquisition system. The CLEO III detector is expected to record an integrated luminosity of 75 fb^{-1} by the year 2003.

The goals of CLEO III are

- Measurement of the weak phase γ with a precision of 15° modulo theoretical uncertainties.

- Measurement of $|V_{ub}|f_B$ with a precision of 10% using $B \to \ell\nu$,

- Measurement of $|V_{td}|$ with a precision of 15% (stat.) using $B \to \rho\gamma$,

- Measurement of $|V_{ub}|$ and $|V_{cb}|$ with precisions of 10% and 4% respectively,

- Measurement of the branching fraction for $b \to s\gamma$ with a precision approaching 8%,

- Discovery of $B \to K^*\ell^+\ell^-$ if it occurs at the rate predicted by the Standard Model.

In addition, CLEO III will explore the dynamics of B decays and will search for rare decays with a sensitivity approaching 10^{-6}.

CDF

CDF installed a silicon microvertex detector, called SVX, and took data with it in the running period from 1992 to 1996, called Run I. The integrated luminosity was $\sim$110 pb^{-1}. The trigger for B events used the presence of leptons in the final state. The SVX detector enabled CDF to exploit the high B cross section at the Tevatron to do excellent B physics, including

- Observation of the B_s and Λ_b in exclusive decay modes;

- Measurement of the transverse momentum dependence of the $b\bar{b}$ cross section in the central rapidity region;

- Measurement of the lifetimes of the B^0, B^+, B_s, and Λ_b with accuracy comparable to the world averages;

- Time-dependent studies of B^0–$\bar{B}^0$ mixing;

- Search for rare decays; and

- Evidence for B_c.

In carrying out these measurements, CDF demonstrated all of the elements necessary to observe CP violation and, in particular, to measure $\sin 2\beta$:

- Ability to reconstruct exclusive decays such as $B^0 \to J/\psi(\mu^+\mu^-)K_S(\pi^+\pi^-)$ with good signal to background;

- Ability to measure the proper time distribution of the B decays; and

- Ability to 'tag' the flavor of the signal hadron at the instant of production.

CDF's work on tagging is especially important. It has generally been assumed that only lepton tagging would work in a hadronic environment. Lepton tagging is not very efficient because the leptonic branching fraction is only about 20% and it is necessary to place relatively stringent cuts on the leptons to eliminate backgrounds. CDF demonstrated that it was possible to achieve good tagging efficiency using a variety of approaches:

- The 'classical' away-side muon and electron tag;

- The jet charge of the opposite-side B hadron; and

- Same side pion tag, which exploits the correlation between the B flavor and the pions from the fragmentation (non-resonant or via resonances) of the b parent quark.

Using all these tags and accounting for mistags and tag overlaps, the 'effective tagging efficiency,' ϵD^2, achieved in Run I was about 2.8%.

The CDF detector is being upgraded for the next Tevatron run, Run II, to handle the much higher rates and shorter interval between beam crossings. Many aspects of the upgrade will result in improved B-physics capabilities. A major improvement will be the new silicon vertex detector, SVX II. This detector has better acceptance and both $r - \phi$ and $r - z$ readout, which allows 3D vertex reconstruction. The readout is deadtimeless and the SVX II information is available to the Level II trigger. The trigger will be much more efficient for B decays. There will be a Level I track trigger based on the outer tracker in addition to the lepton triggers, which will improve sensitivity

to all-hadronic modes such as $B^0 \to \pi^+\pi^-$. The Level II trigger will use hits from the SVX to derive impact parameter information for use in selecting B decays. There is also room to add a time-of-flight detector to allow flavor tagging with away-side kaons. The effect of these changes will be to raise the overall efficiency and to improve the effective tagging efficiency to 5.4% (or 7.8% with kaon tagging). CDF has used its Run I results and the projected improvements to predict its accuracy for measuring $\sin 2\beta$, the asymmetry in $B^0 \to \pi^+\pi^-$, x_s, and the branching fractions (or limits) for various rare B decays during Run II, whose integrated luminosity is expected to be 2 fb^{-1}. Beyond that, there is the possibility of a Run III, which would have an integrated luminosity of 20 fb^{-1}. To run at such high luminosity, the inner layers of the silicon strip detector will need to be replaced, possibly with pixel detectors.

D0

The D0 experiment had its first run from 1992 to 1995. During this run, the detector did not have a magnetic field or a precision vertex detector so its B-physics measurements were limited to production studies using leptons and a search for rare decays involving dimuons. The B cross section was measured out to a rapidity of 3, using various signatures at $\sqrt{s} = 1.8$ TeV and $\sqrt{s} = 630$ GeV. A 90% confidence level upper limit of 3.2×10^{-4} was placed on the rare decay $b \to X_s\mu^+\mu^-$.

The detector is being upgraded with

- The addition of a solenoid to provide a central magnetic field;

- The addition of a silicon microvertex tracker consisting of 4 barrel layers and forward disks;

- A silicon track trigger at Level II; and

- Several improvements to the muon system.

With these improvements, D0 can address a much broader range of B-physics topics in Tevatron Run II beginning in the year 2000. Possible topics include the measurement of individual B meson and baryon masses and lifetimes; measurement of $\sin 2\beta$ through the decay $B^0 \to J/\psi K_S^0$; search for B_s mixing; studies of the B_c meson; and search for rare decay $b \to X_s\mu^+\mu^-$.

Simulations of the measurement of $\sin 2\beta$ give, for $2\,\text{fb}^{-1}$, $\delta(\sin 2\beta) = 0.28$ using only muon tags or $\delta(\sin 2\beta) = 0.15$ if other tagging algorithms – jet charge, same side pion, and electrons – can be made to work in D0. B_s mixing can be observed if x_s is in the range 12–16.

In order to improve its capabilities for B physics, D0 wants to implement a Level II impact parameter trigger. It has applied for MRI funding from NSF to carry this out.

HERA-B

HERA-B is a fixed target experiment that uses the halo protons from the HERA Electron-Proton Collider interacting in thin wires (Al, Cu, or C) outside the main beam. This works because the ≥ 920 GeV protons leaving the beam core diffuse outwards very slowly, stay in the machine, and make multiple traversals of the thin targets before they are lost so that a large fraction of the halo protons eventually interact. It has been possible to achieve interaction rates of 40 MHz using two sets of 4 wires, arranged in a square, separated longitudinally. This configuration produces 4×10^{14} interactions per year and about 3×10^8 B pairs, assuming a 10 nb cross section. The average number of interactions per beam crossing with the target is 5.

One advantage of HERA-B is that the B's are produced at very high momentum, more than 100 GeV, and travel a long way, of order 10 mm, from the very well-localized (in z) interaction vertex. Although many interactions occur each crossing, there are really eight separate target segments, which helps the silicon tracking system resolve the various vertices and correctly associate tracks with them.

B decays are detected by a silicon strip detector located just downstream of the wire targets. Following this, there is a large spectrometer magnet with drift chambers and microstrip gas detectors and straw tube chambers in and downstream of it for tracking and momentum reconstruction. This is followed by a gas ring-imaging Cerenkov counter with multi-anode photomultiplier readout, a transition radiation detector, electromagnetic and hadronic calorimeters and a muon detector. The segmented target and its small z extent assist in sorting out the primary and secondary vertices. In order to maintain good tracking efficiency with an average of 5 interactions per crossing, the detector is very highly segmented so that the average occupancy is never very high.

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The trigger is also a challenge. It begins with a pre-trigger based on signals from the so-called 'fast' devices: the EM calorimeter, muon chambers, and pad chambers, to identify Regions of Interest (ROI's) containing electrons, muons, or high P_t hadrons from B decays. At the second level, the ROI's are inspected for tracks downstream of the magnet. At Levels III and IV, the silicon information is brought to bear to improve the track parameters and to permit more stringent cuts. Finally, a full event reconstruction is carried out including information outside the original ROI. With this system, which is both pipelined and parallel, the event rate will be reduced to approximately 25 Hz for recording to archival storage for off-line analysis.

Because of the relatively low numbers of produced B's this experiment has as its primary goal the measurement of $\sin 2\beta$ and perhaps the asymmetry in the decay of $B^0 \to \pi^+\pi^-$. It also should measure many B-decay modes, including the decays of B_s and B baryons and it should be able to measure B lifetimes very well.

4.2.2   Stage III: Experiments that would start after 2003

By 2003, we will have determined $\sin 2\beta$ with a precision of ± 0.10 (or better if the BaBar TDR estimate of ± 0.059 is borne out), the asymmetry in $B \to \pi^+\pi^-$ not quite so well, and studied γ through the decays $B \to K\pi$ (see Sec. ??), and we will have halved the current uncertainties in the magnitudes of the CKM matrix elements V_{ub}, V_{cb} and V_{td}. We will also have advanced our understanding of the dynamics of B decays far beyond its current state. We may also have observed $B \to K^*\ell^+\ell^-$. Much of the important physics, however, will remain untouched. The remaining goals will include observation of direct CP violation, precision measurement of the weak phase γ, detailed studies of the magnitudes and phases of loop decays such as $b \to s\ell^+\ell^-$, detailed studies of CP violation in B_s decays, studies of b baryons and B_c mesons, and rare charm decays, including, possibly, observation of CP violation in charm decay. Possibly Δm_s will be undetermined, as well.

Potential experiments during this period include both e^+e^- colliders operating at the $\Upsilon(4S)$ and experiments at hadron colliders. Among the e^+e^- colliders, both CESR and PEP-II are exploring upgrades to a luminosity of $3 \times 10^{34} \mathrm{cm}^{-2}\mathrm{s}^{-1}$. Among hadron experiments, ATLAS and CMS are likely to pursue B physics during their first years of operation. In addition, BTeV at FNAL and LHCb at CERN are proposals for detectors optimized for B

physics.

BTeV

BTeV is designed to run in the C0 interaction region, which is under construction at the Fermilab Tevatron, where the luminosity will be $2 \times 10^{32}\text{cm}^{-2}\text{s}^{-1}$ with a bunch crossing interval of 132 ns. The luminous region will have a σ_z of 30 cm.

The key design features of BTeV are:

- A dipole located on the intersection region, which gives BTeV effectively two spectrometers – one covering the forward rapidity region and one covering the backward rapidity region. The angular acceptance is from ± 10 to ± 300 mr in both arms;

- A precision vertex detector based on planar pixel arrays;

- A vertex/impact parameter trigger at Level I, which makes BTeV especially efficient for states with no leptons in them; and

- Particle identification based on a ring-imaging Cerenkov counter, which also provides tagging by kaons.

The pixel microvertex detector is necessary because the vertex detector must be placed as close to the beam as possible to achieve the best resolution. It must deal with high radiation levels and high occupancy. In the current design, the pixels will come within 6 mm of the beam. The pixel detector will provide space points that can be used in the trigger and in the analysis. The pixel readout is designed to deliver its hits to a fast trigger processor, which forms the Level I trigger. A pixel detector on the scale of those planned for ATLAS and CMS, incorporated into the Level I trigger is an ambitious design. It would enable BTeV to remain competitive even after LHC begins running. The technical challenge here is very great.

Particle identification is based on a gas ring-imaging Cerenkov counter. In the current design, efficient particle identification extends from 3 GeV to 70 GeV. The use of aerogel on the front window of the RICH is being investigated. Powerful charged-hadron identification is essential to carry out many of the key measurements and is one of the features that differentiate BTeV (and LHCb) from CDF, D0, ATLAS, and CMS at the Tevatron and the LHC.

The experiment also has muon detectors and electromagnetic calorimeters, which are used in lepton identification and triggering.

BTeV has recently been officially recognized "as an approved R&D project for a dedicated Tevatron collider heavy-quark experimental program". The collaboration has developed an R&D plan and submitted it to the NSF and DOE. There are four R&D efforts defined at present: pixel R&D; trigger R&D; particle identification R&D; and muon detector R&D. The pixel effort is part of a collaborative effort with Fermilab, several universities, other HEP laboratories, and industrial partners.

LHCb

LHCb will take advantage of the large cross section, $\sim$500 μb, to study CP violation in B decays. It will run at a luminosity of $2 \times 10^{32}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ with a bunch crossing interval of 25 ns. Initially triggering will be limited to crossings with single interactions.

The spectrometer is based on a forward dipole with angular coverage from 10–300 mr. The vertex detector is a silicon strip detector with an $r - \phi$ geometry. The vertex detector and the interaction point are upstream of the dipole. The particle identification is done with two ring-imaging Cerenkov counters. One is an 'aerogel-gas combination RICH' located upstream of the spectrometer dipole. The aerogel radiator provides coverage of the momentum interval from 1.4 to 12 GeV. The gas radiator covers from 8 GeV to 80 GeV. The second particle identifier, a gas RICH, is located downstream of the dipole just before the electromagnetic calorimeter. It covers the momentum interval from 16 to 120 GeV. The spectrometer has an electromagnetic calorimeter, a hadron calorimeter, and muon detector.

The trigger has four levels. The first level selects events with muons, electrons, or high transverse-momentum hadrons. The second level uses tracking and vertex topology. The third level combines detector elements to further reduce the rate. The fourth level does a partial (or perhaps a full) event reconstruction to select a sample of B final states for archiving to permanent storage. The trigger has been carefully simulated and the trigger strategy has recently been optimized. The tagging strategy is based on muons with $p_t \geq 1.25\,\mathrm{GeV}$, electrons with $p_t \geq 1.25\,\mathrm{GeV}$, and non-primary kaons. Detailed studies of tagging efficiency and mistags have been performed.

ATLAS and CMS

Both ATLAS and CMS plan to do B physics, especially in early running

at LHC when the luminosity is likely to be relatively low. Both detectors feature pixel vertex detectors, precision trackers, and lepton identification. This suits particularly well the measurement of $\sin 2\beta$, $\Delta m_s = x_s \Gamma_s$, and rare decays like $B^+ \to K^+ \mu^+ \mu^-$. For example, ATLAS anticipates measuring $\sin 2\beta$ to ± 0.017, x_s out to 38, and observing a signal of 680 events of $B \to \mu^+ \mu^- K^{*0}$ over a background of 185 events, assuming the Standard Model prediction of $BR = 1.5 \times 10^{-6}$ [?]. The measurement of α in $B \to \pi^+ \pi^-$ is handicapped both by the potential for penguin contributions and by the lack of particle identification to reject the important $K\pi$ background. Lack of particle identification is also a problem for the measurement of γ.

<u>CESR Phase IV</u>

There is an active program exploring the feasibility of a luminosity of $3 \times 10^{34} \mathrm{cm}^{-2}\mathrm{s}^{-1}$ at CESR. The luminosity in Phase III (starting in 1999) of $1.7 \times 10^{33} \mathrm{cm}^{-2}\mathrm{s}^{-1}$ will be achieved with electron and positron beams sharing the same beam pipe, with multiple bunches in each beam. To avoid collisions away from the CLEO interaction region, the beams are in pretzel orbits; however, long range interactions at the crossover points will ultimately limit the current and tune shift. Higher luminosities will require separating the electron and positron beams into their own rings.

Preliminary designs use compact dual-aperture dipole, quadrupole, and sextupole magnets. The magnets may be superconducting, with the quadrupoles and sextupoles in a half-cell sharing a cryostat. A first prototype quadrupole has been constructed using NbTi wire; high-T_c superconducting wire (BSC-CO) is also under investigation, as it would allow a simpler cryogenic system. Novel techniques to shorten bunch length and to raise the tune shift by using round beams are also under study, and will make use of beam tests in CESR.

Achieving very high luminosity will require other technical advances. Vacuum systems will have to provide very high pumping speeds and low wakefield impedance. Crotches, sliding joints, and separators will have to withstand high synchrotron radiation levels. Finally, the superconducting RF systems will have to deliver very high power while maintaining low impedance to reduce higher modes that can destabilize the beam.

The CLEO detector would be largely unchanged from its Phase III configuration; however, some improvements may be desirable. Modified elements might include the vertex detector, the CsI crystals nearest the beam, the muon steel, and some of the readout and data acquisition electronics.

<u>Upgraded PEP-II</u>

The PEP-II accelerator team is working on a plan for upgrading PEP-II to achieve luminosities that are higher than the initial design of $3 \times 10^{33} \mathrm{cm}^{-2}\mathrm{s}^{-1}$. While adiabatically improving the performance of PEP-II during the first few years of running (1999-2002), they plan to work on detailed designs to achieve a luminosity of $10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ (Phase I) and ultimately $3 \times 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ (Phase II). Achieving the design luminosity for Phase I will require some combination of increased currents, lower β_y^*, higher tune shift, and relaxed energy transparency conditions. The Phase II design luminosity will most likely require all of these changes, and could require rebuilding the interaction region to accommodate a nonzero crossing angle at the collision point.

4.3   Comparison of Experiments

Estimates of the capabilities of the various experiments for measuring the sides of the unitarity triangle, β, α, γ, x_s, and $b \to s\ell^+\ell^-$ are given in Tables ??, ??, ??, ??, ??, and ??. The numbers in the Tables were drawn from presentations to the Panel, from design reports, and from publicly available documents. Though not listed separately, BELLE is expected to perform similarly to BaBar. Detailed direct comparisons are inappropriate because the studies vary in the degree to which they incorporate backgrounds and other important limitations. Some estimates will likely turn out to have been too optimistic. In other instances, improvements will be made and the performance achieved may surpass what is predicted at present. Nonetheless, the Tables provide a general guide to the performance that we can expect from the various kinds of experiments.

By the end of Stage II, measurements of the magnitudes of the sides of the unitarity triangle should reveal whether the CKM matrix is real or complex and whether it fully accounts for the CP violation observed in the kaon system (see Fig. 3).

By far the most amenable study of CP violation is the measurement of $\sin 2\beta$. All the experiments considered, except CLEO, expect to measure it. At Stage II, we can anticipate its determination to about ± 0.10 or better.

The angle α is much less tractable. The low branching ratio for $B \to \pi^+\pi^-$ is an especially serious problem for e^+e^- machines. Particle identification is a problem for CDF and D0. Penguin contributions are a problem for every experiment. The known solutions are isospin analysis and measuring

$B^0 \to \rho\pi$. Both of these require reconstructing final states with π^0's, perhaps excluding all but e^+e^- experiments. Possibly there will be independent information about the penguin contributions. This might make it possible to use the high precision data on the asymmetry in $B \to \pi^+\pi^-$ to determine $\sin 2\alpha$. High statistics at an e^+e^- machine may be the surest means of finding α itself to high precision.

The angle γ can be attacked even without time-dependent measurements in the channels $B \to K\pi$. However, this analysis depends on some assumptions about final-state interactions, which limit the reliability of the method. Independent information about final-state interactions could make this method quite effective. The alternative methods involve $B_s \to D_s^{\pm}K^{\mp}$ and $B^- \to DK^-$ and are the province of BTeV and LHC b.

The measurement of the mass difference between the B_s eigenstates has already been carried to $x_s = \Delta m_s \tau_b > 16$ by LEP experiments. CDF and D0 should expand this somewhat in Run II. The first real measurement of x_s might well come at BTeV or at LHC.

The measurement of rare B decays is in its infancy. While the e^+e^- machines should be able to measure a branching ratio for $B \to K^*\ell^+\ell^-$ in Stage II, the hadron machines with their enormous event rates inevitably have an advantage here. They should be able to measure such processes in detail and seek out rarer processes. Theoretically, the most useful information is provided by the inclusive decay $b \to s\ell^+\ell^-$. The inclusive mode is best studied at e^+e^- machines.

What is less easy to display in tables is the broad scope of B physics that will be explored in all these experiments. The measurement of $\sin 2\beta$ is remarkably clean but it is unique among the CP measurements. Most other CP violation effects are obscured by hadronic uncertainties. However, by measuring a multitude of B decays, their systematics may become clearer. If, for example, final-state interactions turn out to be small everywhere they are measured, it will be possible to simplify the analyses for α and γ. Alternatively, we may learn enough about penguin contributions to provide powerful input for these analyses.

Magnitudes of CKM Matrix Elements			
	Precision	Technique	Comments
BaBar			Similar to CLEO
CLEO	$|V_{ub}|$ to $\pm10\%$	$B \to \pi\ell\nu,\ \rho\ell\nu$	Reliable lattice calculation required for this precision
	$|V_{ub}/V_{td}|$ to $\pm12\%$	$B \to \ell\nu$	Combine with B^0–$\bar{B}^0$ mixing
	$|V_{ts}/V_{td}|$ to $\pm15\%$	$B \to \gamma\rho, \omega, K^*$	
CDF	$|V_{ts}/V_{td}|$	From x_s/x_d	See below
D0	$|V_{ts}/V_{td}|$	From x_s/x_d	See below
HERA-B			
BTeV	$|V_{ts}/V_{td}|$	From x_s/x_d	See below
	$|V_{ts}/V_{td}|$	$B \to \mu^+\mu^- K^{*0}, \rho^0$	Should surpass ATLAS, CMS because of particle id
ATLAS	$|V_{ts}/V_{td}|$ to $\pm11\%$	$B \to \mu^+\mu^- K^{*0}, \rho^0$	[?]
CMS	$|V_{ts}/V_{td}|$ to $\pm3.5\%$	$B \to \mu^+\mu^- K^{*0}, \rho^0$	[?]
LHCb	$|V_{ts}/V_{td}|$	From x_s/x_d	See below
	$|V_{ts}/V_{td}|$	$B \to \mu^+\mu^- K^{*0}, \rho^0$	Should surpass ATLAS, CMS because of particle id

Table 8: Claims of the various experiments for their ability to measure magnitudes of some of the CKM matrix elements. The CLEO numbers are predicated on an integrated luminosity of 75 fb^{-1}. The hadron colliders can measure Δm_s directly (see Table **??**) if it is within their reach. If Δm_s is too large, it may be measured indirectly by measuring $\Delta\Gamma_s$, the lifetime difference of the B_s mass eigenstates. This approach introduces theoretical uncertainties as well as the problem of measuring $\Delta\Gamma_s$. CDF claims this would allow a $\pm20\%$ measurement of $|V_{td}/V_{ts}|$ [**?**]. LHCb is more circumspect, claiming only that the $\Delta\Gamma_s$ route "will provide an indirect measurement of Δm_s within the Standard Model, although with a large uncertainty" [**?**]. The larger direct Δm_s reach of BTeV and LHCb gives them the advantage here. The errors on the ATLAS and CMS numbers are statistical only. The error on the CLEO measurement of $|V_{ts}/V_{td}|$ is also statistical.

sin 2β			
	Precision	Technique	Comments
BaBar	± 0.059 @ 30 fb^{-1} ± 0.019 @ 300 fb^{-1}	$J/\psi K_S$, $D^+ D^-$, etc.	Estimates from TDR [?]
CLEO			
CDF	± 0.09 @ 2 fb^{-1} ± 0.076 @ 2 fb^{-1}	$J/\psi K_S$ $J/\psi K_S$	Without time-of-flight. With time-of-flight. From CDF II TDR [?]
D0	± 0.16	$J/\psi K_S$	From [?]
HERA-B	± 0.13	$J/\psi K_S$	From [?]
BTeV	± 0.015	$J/\psi K_S$	From [?]
ATLAS	± 0.017	$J/\psi K_S$	From [?]
CMS	± 0.023	$J/\psi K_S$	From [?]
LHCb	$\pm(0.017 - 0.011)$	$J/\psi K_S$	From [?]

Table 9: Claims of the various experiments for their ability to measure $\sin 2\beta$.

sin 2α			
	Precision	Technique	Comments
BaBar	± 0.085 @ 30 fb^{-1}	$\pi^+\pi^-$, $\rho\pi$, $a_1\pi$, etc.	Estimates from TDR [?]. Measure α even with penguins.
CLEO			
CDF	± 0.10 @ 2 fb $^{-1}$	$\pi^+\pi^-$	With time-of-flight. Uses dE/dx from drift chamber. Measures asymmetry only [?].
D0			No K/π separation
HERA-B	± 0.22	$\pi^+\pi^-$	From [?] Measures asymmetry only.
BTeV	± 0.03	$\pi^+\pi^-$	From [?] Measures asymmetry only.
ATLAS	± 0.18	$\pi^+\pi^-$	From [?] Measures asymmetry only.
CMS	± 0.16	$\pi^+\pi^-$	From [?] Measures asymmetry only.
LHCb	± 0.05	$\pi^+\pi^-$	From [?] Measures asymmetry only.

Table 10: Claims of the various experiments for their ability to measure sin 2α in $B \to \pi^+\pi^-$ itself. Because of the likely contribution from penguin diaguims, whose weak phase differs from that of the tree diagrams, the analysis is much more difficult than for sin 2β. The asymmetry by itself does not determine sin 2α, though the precision indicated in the Table represents the uncertainty in sin 2α computed as if there were no penguins. In principle, using isospin symmetry and measuring the time-dependent (tagged) decay to $\pi^+\pi^-$, together with the branching ratios to $\pi^0\pi^0$, $\pi^\pm\pi^0$, suffice to find α, up to discrete ambiguities, even in the presence of penguin amplitudes. CESR can contribute by measuring the decays without time dependence. Unfortunately, a very small branching ratio is expected for $B \to \pi^0\pi^0$, making this approach problematic. More promising is the use of $B \to \rho\pi$, though again a small branching ratio to $\rho^0\pi^0$ may impede this program and require extensive running. It is assumed that the hadron colliders will not measure modes with π^0's, although LHCb has begun consideration of the $\rho\pi$ channel [?].

γ			
	Precision	Technique	Comments
BaBar			Similar to CLEO
CLEO	$\pm 30°$ @14fb^{-1} $\pm 15°$ @75fb^{-1} $\pm 10°$ @300fb^{-1}	$K\pi$ $K\pi$ $K\pi$	For theoretical uncertainties see Section ??.
CDF			
D0			
HERA-B			
BTeV	$\sigma(\sin\gamma) \approx \pm 0.10$ $\sigma(\gamma) \approx \pm 8°$	$B_s \to D_s K^{\pm}$ $B^- \to \bar{D}^0 K^-$ $B \to K\pi$	Measures $\sin(\gamma \pm \delta)$ [?]
ATLAS	uncertain	$B \to DK$	Analysis in progress
CMS	unknown		
LHCb	$\sigma(\gamma) \approx \pm 10°$	$B_s \to D_s K^{\pm}$	[?]

Table 11: Claims of the various experiments for their ability to measure the angle γ in the unitarity triangle.

Δm_s and x_s			
	Precision	Technique	Comments
BaBar			
CLEO			
CDF	Measure if $x_s \leq 20$	$B_s \to D_s n\pi$	[?]
D0	Measure if $x_s \leq 16$	$B_s \to D_s n\pi$	[?]
HERA-B			
BTeV	Measure if $x_s \leq 40$	$B_s \to D_s \pi$	EOI configuration
	Measure if $x_s \leq 80$	$B_s \to D_s \pi$	Square hole pixel design
ATLAS	Measure if $x_s \leq 38$	$B_s \to D_s \pi, a_1$	[?]
CMS	Measure if $x_s \leq 38$	$B_s \to D_s \pi$	[?]
LHCb	Measure if $x_s \leq 91$	$B_s \to D_s \pi$	[?]

Table 12: Claims of the various experiments for their ability to measure the mass difference Δm_s and the corresponding mixing parameter x_s.

$B \to K\ell^+\ell^-$, $b \to s\ell^+\ell^-$			
	Precision	Technique	Comments
BaBar			Similar to CLEO
CLEO	Rate to $\pm 30\%$ @ 75 fb^{-1} $\pm 10\%$ @ 600 fb^{-1} Observable @ 75 fb^{-1}	$B \to K^*\ell^+\ell^-$ $b \to s\ell^+\ell^-$	[?]
CDF	100 to 300 events 400 to 1100 events Reach at least 2×10^{-7}	$B^+ \to \mu^+\mu^- K^+$ $B^0 \to \mu^+\mu^- K^{*0}$	[?]
D0	Reach at least 4×10^{-6}		[?]
HERA-B			
BTeV	2400 events	$B^\pm \to \mu^+\mu^- K^\pm$	[?]
ATLAS	680 events	$B^0 \to \mu^+\mu^- K^{*0}$	[?]
CMS	4200 events	$B^0 \to \mu^+\mu^- K^{*0}$	[?]
LHCb	Significant capability		No explicit number in [?]

Table 13: Claims of the various experiments for their ability to measure some decays of the form $b \to s\ell^+\ell^-$. The inclusive measurement would be theoretically cleaner. The anticipated rates are based on Standard Model predictions.

5   The Further Development of B Physics

Much of the B-physics program is already underway or scheduled to begin soon in Stage II described above. CLEO will be running in 1998, and again in 1999 after installation of the upgrade that transforms it into CLEO III. In 1999 as well, HERA-B will begin operation, as will the B factories BaBar and BELLE. These will be followed by the upgraded CDF and D0 detectors, which will begin running with the Main Injector in 2000.

Further opportunities to expand B physics in Stage III may occur beginning around 2004. BTeV could begin operating at that time, while LHC-B could turn on at the beginning of LHC running, scheduled for 2005. High luminosity e^+e^- running at a symmetric or an asymmetric B factory might also be anticipated in the interval from 2004 to 2008.

From this chronology and from anticipated luminosities, we can estimate how physics results might unfold. For example, by early 2002, a measurement of $\sin 2\beta$ to ± 0.10 might be available from HERA-B, BaBar, BELLE, CDF, or D0. Simultaneously, CLEO, Babar and BELLE will improve the measurements of the magnitudes of V_{ub} and V_{cb}. Measurements of the time asymmetry in $B \rightarrow \pi^+\pi^-$ would likely come from BaBar and BELLE, roughly two years later, by which time, the result on $\sin 2\beta$ would be considerably improved.

Gradually these results would improve, as the experiments accumulated additional statistics. However, qualitative changes would be unlikely unless new opportunities became available, through greatly increased luminosity at e^+e^- colliders or through new detectors dedicated to B physics. Without these, the full B physics program outlined in Section 2 would remain, at best, half completed. While the measurement of $\sin 2\beta$ would have likely reached very good precision, difficulties in interpreting the $B \rightarrow \pi^+\pi^-$ results make it unlikely that the same could be said of $\sin 2\alpha$ (or of α itself). We will probably not have observed direct CP violation in B decay. The angle γ would be largely unexplored. The value x_s might well be unknown, except for a lower bound of about 20. While our studies of CP violation and rare B decays might already have found evidence for physics beyond the standard model, we would not yet know much about the nature of this physics. The potentially large mass difference between the two B_s mass eigenstates might well not have been measured.

If high luminosity ($> 10^{34}$cm^{-2}s^{-1}) e^+e^- colliders or advanced forward-

geometry B detectors for hadron colliders are to be ready in time to answer these questions, it will be necessary to make decisions around 2001 or so. By that time, there will be evidence on the performance of CESR III and of the asymmetric B factories. The plausibility of increasing their luminosities could then be evaluated. At the same time, we could assess the progress in detector development for BTeV, especially in pixel vertex detectors. Positive decisions on any of these projects would lead to programs that could address the remainder of the B-physics program currently envisioned.

6   Recommendations

The CESR/CLEO effort continues to be one of the most productive in the entire international high-energy program. It has already provided fascinating and important results in B physics. The upgrades of both the accelerator and detector can be expected to provide even more insights into this physics, whose intrinsic value is made apparent by the extensive new investments being made worldwide in new accelerators and detectors. The Panel recommends for the B-physics program that:

- *Full exploitation of the CESR and CLEO upgrades be the highest priority in the immediate future.*

The Panel believes that the B-physics program over the next five to ten years will have as its primary focus a rigorous test of the Standard Model explanation of weak decays. The elements of the Cabibbo-Kobayashi-Maskawa matrix will be measured and, in particular, the sides and angles of the unitarity triangle will be measured. The exploration of CP violation will have a central position in this work, but it will be part of a much larger program that will both provide essential input for the CP work and will explore entirely different avenues. These will include both the systematic study of weak and strong interactions in the multitude of anticipated decays and the thorough exploration of rare decays, both those expected at low rates and those nominally forbidden altogether.

To pursue this full program will require both e^+e^- and hadron-collider experiments beyond those in Stage II. Accordingly, we recommend:

- *NSF should support efforts in both hadron-collider and e^+e^- experiments to explore B physics in the period extending to 2005 and beyond. In particular*

  – Investments should be made in research at CESR to evaluate the prospects for a very high luminosity upgrade, to
  $\mathcal{L} = 3 \times 10^{34} \mathrm{cm}^{-2}\mathrm{s}^{-1}$.

  – Investments should be made in BTeV to enhance the research and development of the challenging technical components required for this very ambitious but promising program.

It is not possible at this time to know how e^+e^- physics will be best pursued once the upgraded CESR and the new accelerators at SLAC and KEK are running. That will depend on their performance, on the prospects for increasing their luminosities and on the opportunities for high-luminosity work at CESR. We recommend that

- *Around 2001 any proposal from CESR for a luminosity upgrade be evaluated in the context of the experience of the asymmetric B factories. If the CESR proposal provides better opportunities than those that would be provided by other e^+e^- machines, NSF should strongly pursue the upgrade.*

While we expect that important B-physics results will be forthcoming from CDF and D0 in the Main Injector run at the Tevatron Collider, in the long term, experiments designed specifically to do B physics will dominate. The BTeV proposal is aggressive both in its schedule and in its design. It seems to have the potential to remain competitive even after the LHC begins to operate. We recommend that

- *Around 2001, a full technical and scientific evaluation of the BTeV experiment should be conducted. If Fermilab proceeds with the BTeV project and if it is competitive with international alternatives, NSF should give it strong support.*

The BTeV program offers an opportunity for NSF to have a major impact on the U.S. high energy physics program both because of its evident potential for attacking important questions in B physics and because there are great

challenges to designing and fabricating the detector, especially in the pixel detector and triggering scheme. An effective program would combine a strong effort from NSF institutions with DOE labs and universities.

The three of the preceding recommendations should be pursued, provided the generally positive expectations for funding in EPP are realized. In particular, NSF should invest enough in the CESR upgrade effort and the BTeV programs to make certain that the evaluations in 2001 will be thoroughly informed.

The Stage II experiments, which will begin taking data in 1999 − 2000, will open a new chapter in the study of CP violation. The observation of CP violation outside the K system would be a landmark result in itself. The quantitative measurement of $\sin 2\beta$ and $\sin 2\alpha$, together with tightened results on the sides of the unitarity triangle will provide important new tests of the standard model. NSF has an important role in this upcoming work. We conclude that:

- *NSF's support of current B-physics research programs (BaBar, CDF, D0, HERA-B) is fully warranted. Arguments for increasing NSF support for the HERA-B program were not persuasive.*

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